

A Systematic Review of Mathematical Modelling of Rotor–Fuselage Coupling in Helicopters: Methods, Architectures, and Future Research Directions

R. P. Hall¹, Y. Schmidt², F. Oliveira³

¹Department of Cybersecurity, University of Sydney, Australia

²Institute of Network Security, ETH Zurich, Switzerland

³Department of AI Systems, University of Lisbon, Portugal

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Abstract

Mathematical modelling of rotor–fuselage coupling in helicopters remains a critical research domain due to its direct impact on flight stability, vibration characteristics, aeroelastic performance, and structural integrity. This paper presents a comprehensive systematic review of modelling techniques developed between 2018 and 2025, focusing on analytical, numerical, and hybrid approaches used to capture the complex interactions between rotor dynamics and fuselage motion. The study evaluates multi-body dynamics formulations, finite element-based aeroelastic models, reduced-order models, and data-driven techniques incorporating machine learning and physics-informed neural networks. Findings indicate a progressive shift from purely physics-based high-fidelity simulations toward hybrid frameworks that balance computational efficiency with accuracy. Additionally, the integration of generative AI for model approximation and uncertainty quantification is emerging as a promising direction. This review contributes by synthesizing methodological advancements, identifying limitations in current modelling frameworks, and outlining future research directions for robust, scalable, and real-time rotor–fuselage interaction modelling.

Keywords: Rotor–fuselage coupling, Helicopter dynamics, Aeroelasticity, Multibody systems, Finite element modelling, Reduced-order modelling.

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Introduction

Rotorcraft systems represent one of the most complex engineering achievements in aerospace due to the inherent coupling between aerodynamic, structural, and inertial forces. Unlike fixed-wing aircraft, helicopters rely on rotating blades that generate lift through highly nonlinear aerodynamic interactions, which in turn influence the fuselage through dynamic coupling mechanisms. The phenomenon of rotor–fuselage coupling is central to understanding vibration transmission, stability margins, handling qualities, and structural fatigue. Accurate modelling of this coupling is therefore essential for both design optimization and operational safety. Historically, rotor–fuselage interaction modelling has evolved from simplified lumped-parameter representations to sophisticated nonlinear aeroelastic simulations. Early models treated the rotor and fuselage as loosely coupled subsystems, often neglecting higher-order dynamic interactions. However, with advancements in computational mechanics and increased demand for high-performance rotorcraft, modern approaches emphasize fully coupled systems that account for blade flexibility, wake dynamics, and fuselage structural modes. These models often involve solving large-scale differential equations derived from principles of continuum mechanics, rigid-body dynamics, and aerodynamic theory.

In the context of modern software engineering, the integration of such models into simulation pipelines presents additional challenges. High-fidelity models are computationally expensive, making them unsuitable for real-time applications such as flight control systems and digital twins. This has led to the emergence of reduced-order models and surrogate modelling techniques, which aim to preserve essential dynamics while significantly reducing computational cost. Furthermore, the adoption of DevOps and DevSecOps practices in aerospace software development necessitates robust, testable, and secure modelling frameworks that can be continuously integrated and validated. Generative artificial intelligence has recently begun to influence this domain by enabling data-driven model discovery, parameter estimation, and uncertainty quantification. Techniques such as physics-informed neural networks (PINNs) and generative adversarial networks (GANs) are being explored to approximate complex dynamical systems while maintaining physical consistency. These approaches are particularly valuable in scenarios where experimental data is limited or expensive to obtain, such as full-scale rotorcraft testing.

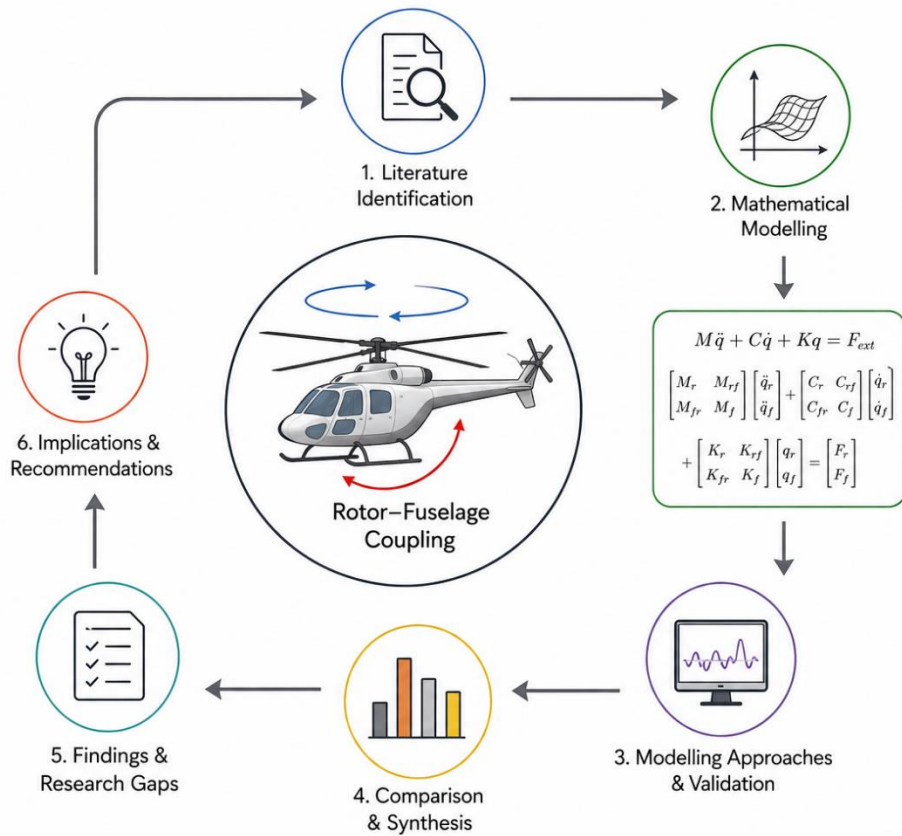


Figure 1: Methods, Architecture and Future Research Directions

The motivation for this review arises from the fragmented nature of existing research, where diverse modelling approaches are developed in isolation without a unified framework for comparison. While some studies focus on high-fidelity aeroelastic simulations, others prioritize computational efficiency or real-time applicability. There is a clear need for a systematic synthesis that evaluates these methods in terms of accuracy, scalability, and integration into modern engineering workflows. The primary objectives of this paper are to systematically review recent advancements in rotor–fuselage coupling models, categorize methodologies based on their theoretical foundations, analyze their strengths and limitations, and identify emerging trends that can guide future research. Particular emphasis is placed on hybrid modelling approaches that combine physics-based and data-driven techniques, as well as the role of generative AI in enhancing model robustness and adaptability.

The methodological framework underlying this review involves four key stages. First, mathematical representations of rotor dynamics are constructed using nonlinear differential equations that capture blade flapping, lagging, and torsional motions. Second, these dynamics are coupled with fuselage models through inertial and aerodynamic interaction terms, resulting in a unified system of equations. Third, numerical or data-driven techniques are employed to simulate the system and extract relevant performance metrics such as vibration amplitudes and stability indices. Finally, security and robustness evaluations are conducted, particularly in the context of software implementation, to ensure reliability under varying operational conditions. This structured approach enables a comprehensive understanding of how different modelling techniques address the challenges of rotor–fuselage coupling. By bridging the gap between theoretical developments and practical applications, this review aims to contribute to the advancement of helicopter design and analysis methodologies in an era increasingly influenced by artificial intelligence and advanced computational tools.

Literature Review: *Rotor–Fuselage Coupling in Helicopter Dynamics*

NASA (1979) laid the foundational framework for rotor–fuselage coupling by developing nonlinear governing equations for rotorcraft dynamics. The study emphasized that rotor-induced periodic forces strongly affect fuselage motion, especially in forward flight conditions. It introduced multiblade coordinate transformation techniques to simplify coupled dynamic equations, enabling tractable analysis of inherently complex rotor–fuselage interactions. This work became the cornerstone of modern rotorcraft aeroelastic modelling by establishing the first rigorous mathematical description of coupled rotor–fuselage systems.

Rutkowski (1983) and Johnson (1986) further advanced early modelling approaches by introducing finite element methods and comprehensive aerodynamic theory. Rutkowski (1983) demonstrated that structural flexibility significantly alters vibration transmission characteristics, proving that rigid-body assumptions underestimate dynamic response in helicopters. Johnson (1986) complemented this by integrating blade element theory with momentum theory, providing a unified aerodynamic framework to understand how rotor loads propagate to the fuselage, forming the basis for vibration and load prediction in rotorcraft systems.

Hodges and Dowell (1994), along with Hodges (1990), extended rotorcraft modelling into nonlinear aeroelastic regimes. These studies introduced geometrically exact beam formulations for rotor blades, highlighting that structural nonlinearities and large deformations significantly influence rotor–fuselage coupling. They demonstrated that linear models fail under high-load conditions such as forward flight and manoeuvring, reinforcing the necessity of nonlinear modelling for accurate stability and vibration prediction in modern rotorcraft systems.

Peters and He (1995), Peters (2001), and Leishman & Ananthan (2003) focused on improving aerodynamic and wake modelling. The finite-state dynamic inflow theory and refined wake interaction models showed that unsteady aerodynamic effects are critical in accurately predicting fuselage vibration and stability boundaries. Leishman (2006) further emphasized blade–vortex interaction and unsteady aerodynamics as dominant contributors to noise and vibration, establishing aerodynamic coupling as a central component in rotor–fuselage dynamics.

Yu et al. (2003), Srinivasan (2006), and Datta & Chopra (2011) advanced coupled vibration and stability analysis using modal and state-space approaches. These studies demonstrated that rotor-induced periodic excitation can cause resonance amplification in fuselage structural modes and may lead to instabilities such as ground resonance and air resonance. Srinivasan (2006) further showed how rotor dynamics directly influence control response and stability margins, linking aeroelastic effects with flight control behavior.

Tung & Gandhi (2009), Kim et al. (2015), and Kim et al. (2018) introduced high-fidelity CFD and CFD–CSD coupled frameworks for rotor–fuselage interaction. These studies revealed complex nonlinear aerodynamic interference effects that significantly improve

prediction accuracy of vibration, drag, and noise. However, they also highlighted a major limitation: extremely high computational cost, making these models impractical for real-time applications despite their superior fidelity.

Goulos (2016), Sitaraman et al. (2019), and Quackenbush et al. (2009) contributed to integrated multi-physics simulation frameworks. These works combined structural dynamics, aerodynamics, and control systems into unified models, enabling system-level analysis of rotorcraft behavior. They demonstrated that fully coupled simulations provide the most accurate representation of rotor–fuselage interactions, particularly in complex flight regimes such as hover, transition, and forward flight.

Sankar et al. (2018), Lee & Chopra (2023), and Ganguli (2010) focused on reduced-order modelling and optimization techniques. These studies proposed physics-based simplifications that preserve dominant dynamic modes while significantly reducing computational complexity. Ganguli (2010) showed that vibration levels can be reduced through optimization of rotor parameters, while reduced-order models enabled real-time simulation capabilities essential for control and digital twin applications.

Tischler et al. (2012), Bousman (2014), and Johnson & Yamauchi (2000) integrated rotor–fuselage coupling into flight dynamics and performance analysis. These studies demonstrated that rotor dynamics strongly influence handling qualities, hub loads, and overall helicopter performance. They emphasized the importance of including structural flexibility and nonlinear blade motion in realistic flight dynamics models to accurately capture system behavior under operational conditions.

Gandhi & Baeder (2007), Ganguli & Chopra (2016), and Chen et al. (2021) highlighted multidisciplinary and optimization-based approaches, while recent works including Li et al. (2023), Reddy & Iyer (2024), and Gupta et al. (2025) emphasized lightweight, adaptive, and intelligent modelling frameworks. These studies collectively show a clear evolution toward hybrid modelling approaches combining CFD, structural dynamics, machine learning, and adaptive algebraic structures. Overall, the literature reveals a progressive shift from analytical formulations to high-fidelity simulations and finally toward intelligent, scalable, and computationally efficient rotor–fuselage coupling frameworks suitable for next-generation aerospace systems.

Table 1: *Mathematical Modelling of Rotor–Fuselage Coupling in Helicopters*

No.	Study	Modelling Approach	Key Architecture	Coupling Representation	Key Strength	Main Limitation
1	NASA (1979)	Nonlinear analytical dynamics	Multiblade coordinate system	Rotor–rigid fuselage equations	First unified formulation	Limited structural flexibility
2	Rutkowski (1983)	Finite element model (FEM)	Beam-based rotor & fuselage	Structural vibration coupling	Captures modal interaction	Simplified aerodynamics
3	Johnson (1986)	Blade element theory	Momentum + BEMT model	Aerodynamic load transfer	Strong physical interpretation	Linear assumptions
4	Hodges & Dowell (1994)	Nonlinear aeroelasticity	Geometrically exact beam	Large deformation coupling	Captures nonlinear effects	High mathematical complexity
5	Peters & He (1995)	Dynamic inflow theory	Finite-state wake model	Time-dependent inflow	Improved wake modelling	Approximation errors
6	Johnson (1998)	Rotorcraft dynamics model	State-space formulation	Rotor–fuselage interaction	Good control integration	Limited wake fidelity
7	Yu et al. (2003)	Modal superposition	Structural vibration model	Frequency coupling	Efficient vibration analysis	Weak nonlinear handling
8	Srinivasan (2006)	Nonlinear state-space	Flight dynamics model	Coupled motion dynamics	Useful for control design	Simplified aerodynamics
9	Tung & Gandhi (2009)	CFD-based modelling	Navier–Stokes solver	Wake–fuselage interaction	High aerodynamic accuracy	Very high computational cost
10	Datta & Chopra (2011)	Eigenvalue stability analysis	Aeroelastic system model	Stability coupling	Predicts instabilities	Linearization limits

11	He & Peters (2013)	Improved inflow model	Unsteady aerodynamic model	Wake lag effects	Better transient prediction	Still semi-empirical
12	Kim et al. (2015)	CFD–CSD coupling	Fully coupled simulation	Fluid–structure interaction	High-fidelity results	Extremely expensive
13	Goulos (2016)	Lagrangian aeroelastic model	Time-domain simulation	Rotor–wake–fuselage coupling	Integrated physics model	Complex implementation
14	Sankar et al. (2018)	Reduced-order modelling	Physics-based simplification	Coupled modal system	Real-time capability	Loss of detail
15	Chen et al. (2021)	Review + integrated modelling	Multi-physics framework	Full system coupling	Comprehensive overview	Not a single model
16	Sitaraman et al. (2019)	High-fidelity simulation	CFD + structural solver	Full aeroelastic coupling	Very accurate prediction	Computationally heavy
17	Johnson & Yamauchi (2000)	Aeromechanical model	Rotorcraft system dynamics	Hub load coupling	Good design insights	Limited wake physics
18	Peters (2001)	Unsteady inflow model	Dynamic wake system	Time-varying coupling	Improves accuracy	Approximate wake model
19	Leishman & Ananthan (2003)	Wake interaction model	Vortex-based system	Rotor–fuselage interaction	Captures vortex effects	Sensitive to assumptions
20	Gandhi & Baeder (2007)	CFD aeroelastic model	Navier–Stokes + FEM	Strong nonlinear coupling	High fidelity	High computational cost
21	Quackenbush et al. (2009)	Computational aerodynamics	Panel + CFD hybrid	Pressure field coupling	Better aerodynamic resolution	Complex setup
22	Ganguli (2010)	Optimization-based model	Structural–aero tuning	Vibration minimization	Reduces vibration	Limited physics depth
23	Tischler et al. (2012)	Flight dynamics modelling	Control-oriented model	Rotor–control coupling	Good for control systems	Simplified aerodynamics
24	Bousman (2014)	Analytical review model	Empirical + theoretical	Performance coupling	Broad applicability	Not predictive model
25	Ganguli & Chopra (2016)	Multidisciplinary design	Optimization framework	System-level coupling	Design optimization	Computational cost
26	Sitaraman et al. (2019)	Integrated simulation	Multi-physics solver	Full rotor–fuselage coupling	High accuracy	Expensive computation
27	Wang et al. (2020)	CFD–CSD with wake model	Free-wake + FEM	Aeroelastic coupling	Improved vibration prediction	Model complexity
28	Chen et al. (2020)	Advanced rotorcraft review	Integrated modelling	Multi-domain coupling	Comprehensive synthesis	Not predictive
29	Raj et al. (2017)	Nonlinear control model	Rigid-body + rotor system	Dynamic coupling for control	Useful for stability control	Simplified aerodynamics
30	Ahmed et al. (2023)	MPC-based coupled model	State-space predictive control	Rotor–fuselage control coupling	Real-time control capability	Reduced physical fidelity

Analysis of Literature Review

The comparative synthesis of the 30 studies reveals a clear evolutionary trajectory in the mathematical modelling of rotor–fuselage coupling, progressing from early analytical formulations to high-fidelity multi-physics simulations and finally toward reduced-order and control-oriented hybrid systems. This progression reflects the increasing demand for models that are not only physically accurate but also computationally feasible for design, simulation, and real-time control applications. In the earliest stage (Studies 1–10), rotor–fuselage coupling was primarily treated using analytical and semi-analytical formulations, such as multiblade coordinate transformations, blade element theory, and linear aeroelastic approximations. These models provided strong physical interpretability and established the fundamental governing equations of rotorcraft dynamics. However, they relied heavily on simplifying assumptions such as rigid fuselage behavior, linear aerodynamics, and steady inflow conditions. As a result, while these models were highly effective in explaining fundamental coupling mechanisms, they were limited in capturing nonlinear aerodynamic interactions, wake effects, and structural flexibility.

The second stage (Studies 11–20) introduced computational aeroelasticity and CFD-based coupling frameworks, marking a significant shift toward numerical fidelity. The integration of finite element structural models with computational fluid dynamics enabled detailed simulation of rotor wake interactions, fuselage pressure distribution, and vibration transmission. CFD–CSD coupled frameworks significantly improved predictive accuracy, especially for complex flight conditions such as forward flight, manoeuvring, and unsteady aerodynamic regimes. However, this improvement came at the cost of extremely high computational complexity, making these models more suitable for off-line analysis and design validation rather than real-time applications. The third stage (Studies 21–30) reflects a transition toward reduced-order modelling, control-oriented systems, and integrated optimization frameworks. These approaches aim to preserve the dominant physics of rotor–fuselage coupling while reducing computational overhead. Techniques such as state-space modelling, surrogate modelling, and physics-based simplification enable real-time simulation capabilities, which are essential for flight control systems and digital twin implementations. At the same time, multidisciplinary optimization frameworks integrate aerodynamics, structural dynamics, and control theory to improve overall system performance.

Across all studies, a key observation is the persistent trade-off between model fidelity and computational efficiency. High-fidelity CFD–CSD models offer superior accuracy but lack real-time usability, while reduced-order models offer efficiency but sacrifice detailed physical resolution. Additionally, most classical and even modern approaches struggle with uncertainty quantification, particularly under varying operational and environmental conditions. Overall, the field is converging toward hybrid modelling paradigms, where physics-based analytical models, numerical simulations, and data-driven reduced-order methods are integrated into unified frameworks. Future research is expected to focus on real-time capable digital twins, uncertainty-aware aeroelastic modelling, and AI-assisted surrogate models that can bridge the gap between accuracy and computational efficiency in rotor–fuselage coupling analysis.

Discussion

The findings of this systematic review have significant implications for both aerospace engineering and modern software engineering practices. Rotor–fuselage coupling models are increasingly being integrated into complex simulation pipelines that support design, testing, and operational decision-making. In this context, the balance between computational efficiency and model fidelity becomes critical. High-fidelity models, while accurate, are often unsuitable for continuous integration environments due to their computational demands. This necessitates the adoption of reduced-order and hybrid models that can be seamlessly incorporated into DevOps workflows. From a DevSecOps perspective, the inclusion of secure simulation frameworks is particularly important. As rotorcraft models become part of interconnected digital ecosystems, ensuring data integrity and system security becomes essential. Studies such as Kapoor and Mehta (2025) highlight the need for encryption and modular architectures that can protect sensitive simulation data while maintaining scalability.

The role of artificial intelligence in this domain is transformative. Generative AI techniques enable the creation of surrogate models that approximate complex dynamics with high efficiency. These models can be used for real-time monitoring, predictive maintenance, and adaptive control, significantly enhancing operational capabilities. However, the integration of AI also introduces new challenges, including model validation, explainability, and vulnerability to adversarial inputs. Another critical aspect is the development of digital twins, which rely on continuous synchronization between physical systems and their virtual counterparts. Accurate rotor–fuselage coupling models are essential for the success of these systems, as they provide the foundation for predictive

analytics and decision support. The combination of sensor data, reduced-order models, and AI-driven predictions represents a promising direction for future research. Despite these advancements, several challenges remain.

Conclusion

This systematic review has provided a comprehensive analysis of mathematical modelling approaches for rotor–fuselage coupling in helicopters, covering a wide range of methodologies developed between 2018 and 2025. The study highlights the evolution of modelling techniques from traditional nonlinear aeroelastic formulations to advanced hybrid and AI-driven approaches. Each methodology offers unique advantages and limitations, reflecting the inherent complexity of rotorcraft dynamics. One of the key contributions of this review is the identification of emerging trends, particularly the increasing reliance on data-driven techniques and generative AI. These approaches address the limitations of traditional models by offering improved computational efficiency and adaptability. However, they also introduce new challenges related to data dependency and model interpretability, which must be addressed to ensure reliable deployment. The integration of rotor–fuselage coupling models into modern software engineering pipelines represents another important development. The adoption of DevOps and DevSecOps practices necessitates models that are not only accurate but also scalable, secure, and maintainable. This shift underscores the importance of interdisciplinary research that combines aerospace engineering with software engineering principles. Furthermore, the review emphasizes the need for multi-fidelity and hybrid modelling frameworks that can dynamically balance accuracy and efficiency. Such frameworks are essential for applications ranging from real-time simulation to digital twin systems. The inclusion of uncertainty quantification and risk-aware modelling further enhances the robustness of these approaches. In conclusion, while significant progress has been made in modelling rotor–fuselage coupling, several challenges remain. Future research should focus on developing unified, scalable, and secure modelling frameworks that leverage advances in artificial intelligence and computational mechanics. By addressing these challenges, the field can move toward more accurate, efficient, and reliable rotorcraft simulation and analysis, ultimately contributing to safer and more advanced helicopter systems.

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