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INTEGRATION OF MULTIPHYSICS METHODS IN AEROSPACE SYSTEM DESIGN: SELECTED CASE STUDIES

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Abstract. *This paper reviews recent approaches to integrating multiphysics modeling in aerospace structural design, focusing on rocket systems. It highlights CFD–FEM coupling, FSI–CHT simulations, and optimization for nozzles and thin-walled components, addressing computational challenges like scale disparity and stiffness. The results offer a concise reference for engineers and researchers in predictive modeling of aerospace structures.*
Keywords: *multiphysics; coupled CFD–FEM analysis; fluid–structure interaction (FSI); conjugate heat transfer (CHT); modeling; multidisciplinary design optimization (MDO)*

Introduction. Multiphysics coupling has become a critical component of predictive modeling in aerospace system design, particularly in rocket engineering, where aerodynamic, structural, and thermal phenomena interact under extreme conditions. The integration of numerical disciplines, however, presents multiple technical and methodological challenges, including the consistency of boundary and initial conditions between independent models, scale disparities of physical processes, mesh adaptivity requirements, stiffness of governing equations, and the considerable computational cost of fully coupled solutions. In practical engineering analysis, hybrid or iterative strategies — such as weak coupling, multiscale and multifidelity frameworks, as well as surrogate-assisted and machine learning accelerated models — provide a feasible compromise between accuracy and computational efficiency. The reviewed literature encompasses case studies focused on ablation and thermal protection modeling (Ewing et al., 2023; Mansour et al., 2024; Piacquadio et al., 2023) [2, 13, 19], nozzle performance and flexible nozzle dynamics (Grossi et al., 2023; Jack et al., 2024; Potier et al., 2022) [3, 7, 20], and aero-thermoelastic or FSI analyses of inlets and hypersonic configurations (Horing et al., 2024; Pandey et al., 2023; Su et al., 2023) [6, 18, 23].

The research aims to evaluate and structure current approaches to multiphysics integration in aerospace structural design — particularly CFD–FEM, FSI, CHT, and ablation modeling for rocket systems — and to propose practical guidelines for engineering use.

The main part. This concise review considered studies on the design and analysis of aerospace structural elements, with emphasis on rocket systems. Publications from 2022–2025 in peer-reviewed journals indexed in Web of Science and Scopus were included. Search terms covered multiphysics modeling, CFD–FEM coupling, fluid–structure interaction, conjugate heat transfer, ablation, and multidisciplinary optimization. Selected studies were evaluated for methodological soundness, relevance to structural design, and insights into computational challenges and integration strategies. To ensure a coherent presentation, the reviewed studies were organized into thematic clusters representing key types of multiphysics integration and their applications in aerospace structural design.

Multiphysics Modeling of Micro- and Advanced Aerospace Structures. Recent studies address coupled multiphysics phenomena in micro- and advanced aerospace components, emphasizing integration of structural, thermal, and optical domains. Li et al. (2023) [9] performed CFD–thermal coupling and geometric optimization of MEMS micronozzles for electrothermal microthrusters, reveal-

ing the strong impact of viscous and conductive losses on thrust efficiency and identifying the limitations of bell-shaped designs at microscale. F. Liu et al. (2024) [11] analyzed the multiphysics mechanical behavior of titanium-coated heterogeneous wings for re-entry vehicles, highlighting fatigue–creep interactions, coating damage mechanisms, and the need for improved predictive models under synergistic thermal, vibrational, and aerodynamic loads. K. Liu et al. (2025) [12] developed an integrated structural–thermal–optical optimization framework for multifunctional photovoltaic concentrators, demonstrating topology-based co-design that balances optical efficiency, thermal management, and structural stiffness for space applications.

Multiphysics Optimization and Machine Learning–Enhanced Design. Recent advances demonstrate how combining physics-based and data-driven approaches enables efficient aerodynamic and aeroelastic optimization under multiphysics constraints. Martins (2022) [14] outlined the evolution of CFD-based design optimization toward open-source, high-fidelity aerodynamic and aerostructural frameworks, establishing methodological benchmarks for the community. Nagawkar et al. (2022) [15] introduced gradient-enhanced multifidelity neural networks that exploit both function and gradient data to reduce computational cost while preserving accuracy in airfoil optimization. Nguyen et al. (2025) [16] proposed the Soft-FEM framework that integrates evolutionary algorithms with adaptive local search to optimize airfoils, wings, and FSI problems, coupling OpenFOAM and MuPhiSim for fluid–structure simulations. Stanford et al. (2025) [22] applied multifidelity optimization with transonic flutter constraints, demonstrating efficient aeroelastic design of flexible wings through trust-region model management combining low- and high-fidelity solvers. Collectively, these studies show the growing convergence of multiphysics modeling, optimization theory, and machine learning in the aerodynamic design of complex aerospace systems.

CFD–FEM Coupling and Aerothermoelastic Simulation. This research direction encompasses solutions to key problems, including the development of fully coupled CFD–FEM approaches for modeling the aerothermoelastic deformations of inlets, which incorporates heat transfer, nonlinear deformation, and the reverse influence of the flow field. Furthermore, multiphysics iteration has been performed for supersonic and hypersonic intake systems, considering various aspect ratios and geometries. The aero-structural behavior of deployable shells in transient regimes has also been investigated. These studies validate the effectiveness of explicit/implicit coupling schemes, adaptive meshing, and consistent boundary conditions for achieving stable convergence and the physically accurate prediction of thermomechanical loads (Horing et al., 2024; Lin et al., 2025; Pandey et al., 2023; Saha et al., 2024; Su et al., 2023) [6, 10, 18, 21, 23].

Conjugate Heat Transfer and Thermal Management in Rocket Systems. In this framework, issues related to coupled heat transfer and thermal flow management in rocket systems have been effectively addressed. CHT approaches were applied to predict heat fluxes in critical engine zones, to optimize the geometry of high-area-ratio nozzles, and to reduce the thermal loads on the skin of hypersonic vehicles. The calculation accuracy was enhanced by combining turbulent gas dynamics with thermal conduction in the walls, which ensures a correct evaluation of interfacial thermal interaction and the effectiveness of thermal protection systems (Habermann et al., 2023; Kumar et al., 2025; Potier et al., 2022; Wang et al., 2025) [4, 8, 20, 25].

Fluid–Structure Interaction and Dynamic Stability of Rocket Components. Building upon this approach, the issues of FSI and the dynamic stability of rocket components have been effectively addressed. An analysis of the aeroelastic response of flexible elements was conducted, the mechanisms of flutter and oscillatory instability were identified, and the influence of shock waves, turbulization, and unsteady loads on structural integrity in high-speed regimes was established (Anton et al., 2023; Jack et al., 2024; Padmanabhan et al., 2023; Pandey et al., 2025) [1, 7, 17, 18].

Ablation and Thermal Protection Modeling. This research direction includes solving problems related to ablation modeling and the assessment of thermal protection system TPS effectiveness, specifically incorporating thermochemical erosion, material gasification, and the aerodynamic impact on structural response (Ewing et al., 2023; Mansour et al., 2024; Piacquadio et al., 2023; Wang et al., 2025) [2, 13, 19, 24].

Hybrid and Experimental Rocket Systems. In this context, effectively resolved problems include examples of problem-solving in areas such as incorporating multiphase effects in solid rocket motor nozzles and the experimental demonstration of a hybrid rocket engine with axial injection, manufactured using the FDM 3D printing technique (Grossi et al., 2023; Hirai et al., 2023) [3, 5].

Conclusions. Analysis of selected case studies demonstrates that coupling Computational Fluid Dynamics with Finite Element Method analyses effectively captures interactions between aerodynamic, thermal, and structural phenomena, although careful attention to mesh compatibility and computational efficiency remains necessary. Fluid–structure interaction simulations provide essential insights into the dynamic behavior of flexible structures under aerodynamic loads, enabling accurate predictions of performance and stability. Conjugate heat transfer modeling allows precise evaluation of temperature distributions and heat fluxes, supporting the design of components that withstand extreme thermal environments. Multidimensional ablation models enhance understanding of material erosion, guiding the development of efficient and durable thermal protection systems, while multidisciplinary optimization facilitates the simultaneous consideration of multiple design objectives to achieve balanced solutions in terms of performance, safety, and cost. *The findings* indicate that adopting hybrid coupling strategies, including weak coupling and multiscale frameworks, can mitigate computational challenges while preserving accuracy. Improving mesh adaptivity in critical regions enhances the resolution of physical phenomena; and employing surrogate models or machine learning–assisted methods can accelerate simulations and support informed design decisions. Incorporating these approaches can advance the predictive capability and efficiency of multiphysics modeling, providing practical guidance for engineers and researchers engaged in aerospace structural design.

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