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High-Fidelity Framework for Fluid–Structure Interaction Analysis of Jet-Engine Turbine Blades Under Vibratory Loading

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Abstract: Aeroelastic interactions play a decisive role in the performance, structural integrity, and service life of turbomachinery components, with jet engine turbine blades being particularly vulnerable due to their exposure to severe aerodynamic and structural loading. Dynamic fluid–structure interactions can excite complex vibration modes, leading to resonance, fatigue, and even catastrophic failure. While the importance of these effects is well recognized, computational investigations remain scarce, and many existing studies rely on specialized, non-generalizable in-house codes. This study bridges that gap by developing a high-fidelity, generalizable computational framework capable of accurately capturing the coupled aeroelastic behavior of turbine blades under realistic vibratory aerodynamic loading. The framework integrates advanced structural dynamics analysis extracting natural frequencies, harmonic responses, and transient behavior—with unsteady Computational Fluid Dynamics (CFD) to resolve time-dependent aerodynamic forces. A tightly coupled two-way Fluid–Structure Interaction (FSI) strategy is employed to fully account for the mutual influence between aerodynamic loading and structural deformation. Validation against available experimental data demonstrates the framework's predictive reliability and robustness. The results yield critical insights into the dynamic response and aeroelastic stability of turbine blades, offering a practical tool for the design and optimization of next-generation aero-propulsion systems with enhanced performance and durability.

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1. Introduction

Jet engines are highly dynamic systems whose performance can deteriorate over time due to inherent vibration characteristics. Among their critical components, turbines play a pivotal role by generating sufficient power to drive the compressor, fan, and auxiliary systems. In designing turbine systems, it is essential to evaluate their structural and aerodynamic behavior under a wide range of loading conditions and to assess performance during various aircraft maneuvers, such as dives, encounters with wind gusts, and rapid throttle changes. These non-periodic aerodynamic loads, and their interaction with turbine components, produce a time-dependent lift distribution across blade surfaces. When these unsteady aerodynamic forces coincide with the natural frequencies of blade rows, they can significantly reduce fatigue life. Even at smaller scales, such unsteady forces act as aeroacoustics source terms, contributing to noise generation. Given these challenges, it is necessary to perform a detailed Fluid–Structure Interaction (FSI) analysis of turbine blades under diverse operational conditions. Such an analysis requires accurate computation of the pressure forces acting on blade surfaces and the resulting structural response. The rotational motion of the turbine and the vibration of its blades lead to strong coupling between the fluid flow and structural dynamics where structural deformation alters the surrounding flow field and, in turn, the altered flow further influences blade motion. This mutual dependence necessitates a tightly coupled two-way FSI analysis.

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