Doctoral Dissertation
Doctoral Program in Aerospace Engineering (38^{th}cycle)

Aeroacoustics of fans for engine cooling in installed conditions

Computational analysis and analytical modeling

By

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Politecnico di Torino
2026

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2026

* This dissertation is presented in partial fulfillment of the requirements for **Ph.D. degree** in the Graduate School of Politecnico di Torino (ScuDo).

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Low-speed axial fans are widely employed in automotive engine cooling systems, where increasingly stringent noise regulations and packaging constraints make aeroacoustic performance a critical design requirement. In practical applications, fan noise generation is strongly influenced by installation effects arising from upstream and downstream components, such as casings, heat exchangers, and measurement environments. However, these effects are often neglected or treated empirically, leading to discrepancies between laboratory measurements, numerical predictions, and in-service acoustic behavior.

This dissertation investigates the aeroacoustic installation effects on a low-speed axial engine cooling fan through a combined high-fidelity numerical and analytical modeling approach. Large-scale simulations based on the Lattice-Boltzmann Method are employed to analyze the impact of measurement environments, flow confinement, and cooling module components on the fan aerodynamics and noise generation mechanisms under both free-blowing and loaded operating conditions. Particular attention is devoted to the role of upstream recirculation, inflow non-uniformities, and tip-region flow separation in shaping tonal and broadband noise sources.

The results demonstrate that experimental and installation settings can substantially alter blade loading, flow topology, and far-field acoustic spectra, introducing artificial tonal components and modifying noise directivity. In installed configurations, the spatial distribution of pressure rise imposed by the heat exchanger and casing features is shown to be a key driver of noise generation, beyond its global aerodynamic effect. While some installation features have a limited influence on mean performance, they strongly affect upstream flow organization and acoustic radiation, highlighting the necessity of system-level aeroacoustic assessment.

Two physics-based noise mitigation strategies are proposed and evaluated: rotating ring shaping to mitigate rotor-backflow interaction noise, and optimized stator vane azimuthal spacing to reduce tonal noise. The study reveals a marked difference in robustness between these approaches, with stator spacing providing consistent

tonal noise reduction across both isolated and installed configurations, while ring shaping exhibits a strong sensitivity to flow confinement.

Building on these findings, an analytical aeroacoustic model is developed to predict tonal and broadband noise sources in low-speed axial fans with rotor-stator interaction. The model explicitly accounts for steady and unsteady aerodynamic loading, leading- and trailing-edge noise mechanisms, and noise redistribution effects induced by uneven blade and vane spacing. A novel potential flow-based velocity reconstruction is introduced and shown to provide an accurate and computationally efficient representation of rotor-stator interaction. The analytical framework is validated against high-fidelity simulations and is shown to reliably predict noise spectra, directivity, and relative sound pressure level variations across operating points and geometrical configurations.

Finally, the validated analytical model is employed in a preliminary coupled aeroacoustic optimization, demonstrating its suitability for low-cost exploration of fan design spaces. Overall, this work advances the understanding of fan noise generation under realistic installation conditions and provides predictive tools and design guidelines to support the development of quieter, high-performance cooling systems.