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Nanoresonator-Based Acoustic Liners for Aircraft Engine Noise Control: A Comprehensive Review of Analytical Modeling, Nanoscale Effects, and Data-Driven Optimization Strategies

T J Prasanna Kumar[1], K Sivajibabu[2], B Durga Prasad[1]

[1*]Department of Mechanical Engineering, Jawaharlal Nehru Technological University Anantapur, Ananthapuramu, India
[2]Department of Mechanical Engineering, Prasad V Potluri Siddhartha Institute of Technology, Vijayawada, India
*Corresponding Author Email: tjpk.mech@gmail.com

Abstract

Aircraft engine noise reduction remains a critical challenge due to increasingly stringent environmental regulations and the limitations of conventional passive acoustic liners. Recent advances in nanotechnology and computational intelligence have enabled the development of nanoresonator-based acoustic liners that exhibit enhanced low-frequency attenuation and tunable vibrational characteristics. This review presents a comprehensive and critical assessment of analytical, numerical, experimental, and data-driven approaches used in the design and optimization of acoustic liners, with a particular focus on nanoresonator–nanotube systems. Comparative analysis highlights the role of nonlocal elasticity, wave propagation theory, and polynomial eigenvalue formulations in capturing nanoscale effects that are neglected in classical continuum models. Furthermore, emerging hybrid machine learning optimization techniques are examined for their ability to improve predictive accuracy and design efficiency. The review identifies key research gaps and outlines future directions toward intelligent, adaptive acoustic liners for next-generation aero-engine applications.

Keywords

Acoustic liners; Nanoresonators; Carbon nanotubes; Graphene nanoparticles; Nonlocal elasticity; Machine learning optimization; Aero-engine noise

1. Introduction

Noise generated by aircraft engines is a major contributor to environmental pollution and has significant implications for public health and regulatory compliance. Traditional passive acoustic liners, consisting of perforated face sheets backed by honeycomb cavities, have been widely employed in engine nacelles to attenuate broadband noise. While effective at mid- and high-frequency ranges, these liners exhibit limited performance at low frequencies due to geometric constraints, quarter-wavelength behavior, and material limitations.

To overcome these challenges, research has increasingly focused on advanced liner concepts incorporating resonant elements, acoustic metamaterials, and nanoscale structures. Among these, nanoresonator-based acoustic liners—particularly those employing carbon nanotubes (CNTs) and graphene-based reinforcements—have emerged as promising candidates due to their exceptional mechanical strength, thermal stability, and tunable vibrational properties.

In parallel, the integration of advanced analytical models and artificial intelligence-based optimization algorithms has transformed the design paradigm of acoustic liners. This review consolidates recent developments in nanoresonator-based acoustic liner research and critically compares them with conventional and state-of-the-art approaches reported in the literature.

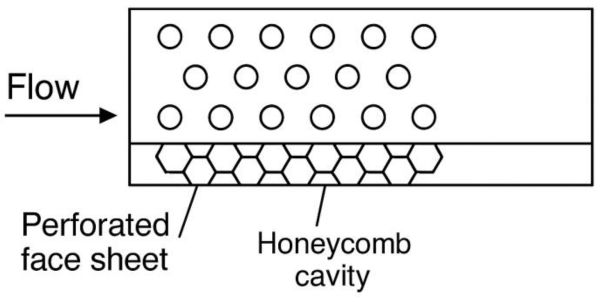

Figure-1: Line Diagram of Acoustic Liner

2. Literature Survey

Aircraft engine noise mitigation has been an active research area for several decades, with acoustic liners forming the primary passive noise-control solution in aero-engine nacelles. Conventional liners typically consist of a perforated face sheet backed by honeycomb cavities and operate on Helmholtz resonance and porous absorption mechanisms. While these liners provide effective attenuation in the mid- and high-frequency ranges, their performance deteriorates at low frequencies due to thickness constraints and quarter-wavelength limitations [1–3].

To overcome these limitations, several studies have focused on improving liner performance through geometric optimization, advanced cavity designs, and flexible wall concepts. Kohlenberg et al. [4] investigated acoustic liners with flexible walls and demonstrated improved broadband attenuation under grazing flow conditions. Similarly, Kenchappa and Shivakumar [5] experimentally evaluated graded microporous acoustic liners on an advanced noise control fan and reported notable improvements in tonal and broadband noise reduction. Despite these advances, such approaches remain constrained by macroscale material properties and do not adequately address low-frequency noise without increasing liner thickness.

In recent years, acoustic metamaterials have emerged as a promising alternative to conventional liners. Metamaterial-based liners utilize locally resonant units, labyrinthine channels, and periodic structures to achieve compact low-frequency attenuation. Comprehensive reviews by Ang et al. [6] and Yao [7] highlight the rapid growth of ventilated acoustic metamaterials, emphasizing their ability to combine airflow permeability with enhanced noise attenuation. Although metamaterial liners show superior low-frequency performance, challenges related to structural complexity, manufacturability, and durability in aero-engine environments persist.

Parallel to metamaterial development, significant attention has been directed toward nano- and micro-scale material enhancements for acoustic absorption. Carbon nanotube (CNT)-reinforced and graphene-based composites have demonstrated superior mechanical, thermal, and acoustic properties compared to conventional porous materials. Xiong et al. [8] reported enhanced broadband sound absorption in multi-walled carbon nanotube (MWCNT)-reinforced foams due to pore microstructure reconstruction and increased viscous dissipation. Ye et al. [9] and subsequent studies [10,11] showed that graphene and graphene-oxide-based composites significantly improve low-frequency absorption through multiscale dissipation mechanisms. These findings indicate that nanomaterials can play a crucial role in next-generation acoustic liners.

Beyond material enhancements, nanoscale resonator concepts have gained importance in vibration and acoustic research. Nanoresonators composed of carbon nanotubes and graphene sheets exhibit strong size-dependent behavior that cannot be captured using classical continuum mechanics. Nonlocal elasticity theory, initially proposed by Eringen, has been widely adopted to model these size effects by incorporating a material length-scale parameter [12,13]. Studies have shown that nonlocal models predict lower natural frequencies than classical models, which is advantageous for low-frequency noise attenuation applications.

Wave propagation theory and spectral finite element methods have also been employed to analyze vibration characteristics of nanoresonator systems. Xu et al. [14] demonstrated that wave propagation-based formulations accurately capture dispersion characteristics and predict lower resonant frequencies compared to traditional eigenvalue approaches. Polynomial and quadratic eigenvalue methods have been used to solve coupled nanobeam and nanotube systems, revealing strong coupling effects between resonators and surrounding media [15]. However, these analytical approaches often involve high computational complexity when extended to large parametric studies.

Recently, the integration of machine learning (ML) and data-driven optimization techniques has transformed the design methodology of vibro-acoustic systems. Reviews by McCarthy et al. [16] and Cerniauskas et al. [17] highlight the increasing use of neural networks and surrogate models for predicting acoustic performance and enabling inverse design of metamaterials. Applied studies have shown that deep neural networks combined with metaheuristic optimization algorithms can significantly reduce computational cost while maintaining high predictive accuracy [18,19]. Such hybrid optimization frameworks are particularly suitable for nanoresonator-based acoustic liners, where the design space is highly nonlinear and multidimensional.

Despite the significant progress reported in the literature, several research gaps remain. Experimental validation of nanoresonator-based acoustic liners under realistic aero-engine operating conditions is limited. Furthermore, multi-physics coupling effects involving thermal, viscous, and flow-induced phenomena are not yet fully explored. The development of adaptive and intelligent acoustic liners incorporating real-time control and data-driven optimization remains an open research challenge.

In this context, the present research contributes by integrating nonlocal and wave propagation theories with graphene-enhanced coupled nanotube nanoresonators and hybrid deep learning optimization, thereby addressing several limitations identified in existing studies.

3. Emergence of Nanoresonator-Based Acoustic Liners

3.1 Motivation for Nanoscale Resonator Integration

Nanoresonators offer distinct advantages over conventional resonant elements due to their high natural frequencies, strong size-dependent behavior, and enhanced sensitivity to thermal and damping effects. Carbon nanotubes and graphene sheets, in particular, exhibit extraordinary stiffness-to-weight ratios and thermal conductivity, making them ideal candidates for next-generation acoustic liner applications.

Unlike traditional liners that rely primarily on geometric tuning, nanoresonator-based liners enable frequency tuning through material parameters, size effects, and boundary conditions, offering unprecedented design flexibility.

4. Comparative Analysis of Analytical Modeling Approaches

4.1 Classical Continuum Models

Classical beam and plate theories have been widely used to analyze resonator vibrations. However, at nanoscale dimensions, these models fail to account for small-scale effects such as long-range atomic interactions, leading to inaccurate predictions of natural frequencies and mode shapes.

4.2 Nonlocal Elasticity Theory

Nonlocal elasticity theory, originally proposed by Eringen, introduces a length-scale parameter to account for size-dependent behavior. Several studies have demonstrated that nonlocal models predict lower natural frequencies compared to classical theories, particularly for CNT-based resonators. This reduction is critical for low-frequency noise attenuation in aero-engine applications.

4.3 Wave Propagation Theory

Wave propagation theory has gained attention as an effective tool for analyzing high-frequency vibrations in nanostructures. Comparative studies reveal that this approach consistently yields the lowest natural frequencies among competing theories, making it particularly suitable for acoustic liner design where low-frequency performance is essential.

4.4 Polynomial Eigenvalue and Governing Equation Approaches

Polynomial eigenvalue formulations offer a mathematically rigorous framework for solving coupled nanobeam systems. While accurate, these methods often predict higher natural frequencies and are computationally intensive, limiting their practical applicability for large parametric studies.

5. Influence of Key Parameters: Insights from Comparative Studies

5.1 Size Effects

Size-dependent parameters significantly influence the vibrational response of nanoresonators. Studies consistently show that increasing the characteristic length scale reduces natural frequencies due to enhanced nonlocal effects. Among commonly investigated scales, a size effect of approximately 2 nm has been found to exert the most pronounced influence.

5.2 Temperature Effects

Thermal loading alters the stiffness and internal energy of nanostructures. Higher temperatures generally increase natural frequencies due to increased thermal excitation, whereas cryogenic conditions suppress vibrational activity, leading to lower frequencies. Optimal performance has been reported at very low temperatures for certain nanoresonator configurations.

5.3 Damping and Viscous Effects

Viscous damping plays a critical role in controlling vibration amplitudes and frequency response. Comparative analyses reveal that increasing damping constants leads to a systematic reduction in natural frequencies, thereby enhancing liner stability and predictive accuracy.

6. Role of Graphene Nanoparticles in Acoustic Liners

The incorporation of graphene nanoparticles into nanoresonator systems represents a significant advancement over CNT-only designs. Graphene enhances stiffness, thermal resistance, and interfacial bonding, resulting in improved vibrational tunability and durability. Existing liner studies rarely explore such nanoscale reinforcements, underscoring the novelty of graphene-integrated nanoresonator liners.

7. Data-Driven and Hybrid Optimization Techniques

7.1 Machine Learning in Vibration and Acoustics

Machine learning models, particularly deep neural networks (DNNs), have demonstrated strong capabilities in capturing nonlinear relationships between system parameters and dynamic responses. These models outperform traditional regression techniques in predictive accuracy.

7.2 Hybrid Metaheuristic Optimization

Hybrid frameworks combining DNNs with nature-inspired optimization algorithms—such as the White Shark Algorithm—have emerged as powerful tools for design optimization. These approaches balance exploration and exploitation, enabling efficient convergence toward optimal parameter configurations.

7.3 Comparative Advantage over Existing Studies

Compared to purely analytical or numerical approaches, hybrid DNN-based optimization significantly reduces prediction error and computational cost. Benchmark comparisons indicate superior performance in terms of RMSE and robustness across varying operating conditions.

Table-1 Comparison of proposed studies with Existing Studies

Category	Traditional Liner Studies	Metamaterials & Resonators	Nano-Enhanced & Data-Driven
Mechanisms	Helmholtz, porous absorption	Local resonances, bandgaps	Nanoresonators, nonlocal effects
Modeling	Classical, FEM	Bandgap & metamaterials design	Nonlocal elasticity + Machine Learning
Materials	Fiberglass, micro-porous media	Engineered periodic structures	CNT, graphene composites
Optimization	Parametric studies	Computational bandgap tuning	ML hybrid surrogate + metaheuristic
Low-Freq Capability	Moderate	Enhanced with resonators	Superior with nanoscale tuning

Compared to traditional designs that primarily focus on geometric optimization and conventional resonators, nanoresonator approaches introduce materials whose mechanical properties and length-scale effects contribute significantly to low-frequency performance. Data-driven hybrid optimization further differentiates these approaches by enabling efficient exploration of expansive parameter spaces.

8. Research Gaps and Future Directions

Despite substantial progress, several challenges remain:

- Lack of experimental validation of nanoresonator-based liners at realistic operating conditions
- Limited studies on adaptive and tunable liners with real-time control
- Need for multi-physics coupling involving thermo-electro-acoustic effects
- Integration of digital twins and online optimization frameworks

Future research should focus on bridging analytical modeling with experimental validation and intelligent control systems to realize smart acoustic liners for next-generation aircraft engines.

9. Conclusions

This review has presented an in-depth comparative analysis of conventional and emerging acoustic liner technologies, with particular emphasis on nanoresonator-based systems. Analytical comparisons highlight the superiority of wave propagation and nonlocal elasticity theories for nanoscale modeling, while data-driven hybrid optimization approaches offer substantial improvements in predictive accuracy and design efficiency. The integration of graphene nanoparticles and machine learning techniques positions nanoresonator-based acoustic liners as a promising solution for low-frequency aero-engine noise mitigation.

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