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Innovative Noise Reduction Techniques in Mechanical Systems: A Review

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Abstract
Mechanical noise reduction has evolved into a multidisciplinary field driven by increasing performance demands, regulatory pressures, and the complexity of modern mechanical systems. This review consolidates advances spanning passive, active, semi-active, hybrid, and AI-enhanced methodologies to provide a comprehensive assessment of current capabilities and emerging opportunities. Basic noise-generation processes- including gear meshing, fluid structure interaction, and aerodynamic excitation are discussed together with the route taken by the noise in mechanical assemblies. Recent progress in materials engineering, including metamaterials, nanostructured composites, and additive-manufactured acoustic structures, has enabled lightweight yet high-performance solutions that overcome the bandwidth and mass limitations of traditional passive treatments. Meanwhile, developments in active noise control, distributed sensing, and adaptive algorithms have expanded controllability across low-frequency and dynamic environments. Integrating smart materials with AI-driven prediction, digital twinning, and multi-objective optimization is reshaping the design of intelligent acoustic systems capable of continuous learning and adaptation. Application-focused innovations in automotive, aerospace, manufacturing, and HVAC systems illustrate how tailored noise-control strategies enhance safety, comfort, and operational efficiency. The review identifies critical research gaps related to the co-design of materials and control architectures, multifunctional acoustic structures, and cross-disciplinary approaches inspired by biological and micro-structured surfaces. Together, these directions signal a transition toward next-generation noise-control solutions that function as adaptive, sustainable, and cyber-physical components within future mechanical systems.

Keywords: Active control, Acoustic materials, Digital twins, Metamaterials, Noise reduction

1. Introduction

The issue of noise control has been a high-priority hotspot of high priority in all contemporary mechanical systems since it is directly related to the safety, comfort, energy consumption, and operational reliability of the system. Automobile, aerospace, manufacturing, HVAC, and robotics are some of the mechanical industries that have become more sophisticated and scaled down in size, which has increased the level of noise production and difficulty in preventing it. Noise exposure from automated processes and manufacturing shifts to increased productivity and closer human-machine integration endangers the health of workers and disrupts the accuracy of the process (Lukodono et al., 2025). Similarly, the utilization of intelligent industrial systems and virtual instrumentation has increased the necessity of sophisticated noise-reduction methods that can be used in real-time operational settings (Martinek et al., 2021). In addition to industrial and engineering factors, the social and environmental reasons have also enhanced the pace of research on the reduction of noise. Noise pollution has been identified to be a public-health issue, and the world stands at the forefront with the WHO and ISO that have put more stringent rules on the allowable exposure limits. These regulations have compelled the industries to reevaluate the conventional noise-reduction practices and acquire more efficient, lightweight, and versatile solutions (Yadegari et al., 2020). In turn, materials, design, and control technologies innovation has become a key avenue to the provision of regulatory requirements and emerging engineering needs.

Noise in mechanical systems is generally considered undesirable or excess sound emanation by dynamic actions, vibration, structure interaction, or fluid movement. Mechanical noise is also accompanied by vibration, and the processes have similar sources and channels of transmission. There is a need to distinguish the concept of sound power (the total amount of acoustic energy produced by a source) and sound pressure (the varying force that is perceived by a sensor or listener) to diagnose and mitigate the problem. These amounts support the analytical models and tools applied in noise evaluation in industries (Martinek et al., 2021). The transmission mechanisms are usually categorized into two, i.e., airborne noise, which spreads by way of fluid media, and structure-borne noise, which passes through the solid components and radiates into the surrounding environment. It is essential to learn the interaction between these paths to develop specific interventions, especially in the high-precision manufacturing lines or metallurgical plants, which are highly mechanized (Butorina et al., 2022). The airborne and structural transmission is frequently coupled in mechanical systems, which need hybrid approaches characterizing the combination of materials engineering, damping technologies, and acoustic design (Gao et al., 2022).

This literature review presents the current innovations in noise-reduction technologies and concentrates on the new interdisciplinary methods. It emphasizes the progress in damping materials, acoustic metamaterials, virtual instrumentation, and cross-sector techniques that can be used in achieving more efficient control of noise. It gives an emphasis on the modern solutions that combine the use of material science, digital control, and mechanical design to attain the increased noise-suppression performance. The review follows a structure that directs the readers through the basic noise-generation processes to the current research on the novel materials, active and hybrid control schemes, and future research prospects that contain the changing requirements of the modern mechanical systems.

2. Sources and Mechanisms of Noise in Mechanical Systems

2.1 Mechanical Noise Generation Mechanisms

A variety of dynamic interactions and operational processes is the cause of mechanical noise in engineered systems. One of the most commonly known contributors is Gear meshing, where the periodic engagement of teeth creates tonal noise and vibration. The dislocation of ideal meshing, i.e., misalignment, wear, or changes in load, enhances excitation forces and radiated noise (Kalifa et al., 2025). Bearings and rotating machinery are also significant sources since roughness of surfaces, lubrication conditions, and dynamic imbalance produce broadband noise components, which spread both by pathways through structures and by air.

Another significant mechanism in fluid-structure interaction is in hydraulic and pneumatic systems. The structural vibrations of the pipes, reservoirs, and valve assemblies are caused by pressure pulsations, turbulent flow, and resonance phenomena and eventually radiate as noise (Fiebig et al., 2018). In energy-intensive applications, there are additional challenges presented by the combustion processes. There are acute acoustic emissions produced by engines and turbines because of the rapid increase of pressure, the turbulent interaction of flames, and flow separation at high speed, which result in both broadband and aerodynamic noise signatures (Bies et al., 2023). These various processes depict how much noise generation has become complicated in a modern mechanically-oriented system and why mitigation should be multi-domain in nature.

2.2 Noise Propagation Pathways

Noise, once generated, propagates to a number of different paths. Airborne transmission. When acoustic waves are radiated into the surrounding media, they are transmitted through air and may be enhanced in strength by enclosures or reflector surfaces. Contrastingly, structure-borne transmission is a vibration energy transfer that exists through solid constituents of frames, shells, and housings. It is an especially difficult route to regulate since structural resonances are the most effective tools when it comes to energy transmission over a long distance with poor attenuation (Bies et al., 2023).

The third route is fluid-borne transmission that is prevalent particularly in hydraulic circuits, piping networks, and fluid reservoirs. Fluctuations in pressure and pulsations of liquids or gases through the fluid column overcome adjoining structures and cause secondary airborne noise (Fiebig et al., 2018). These pathways are important to understand since the effective noise mitigation in many cases involves the presence of several transmission modes that can only be mitigated through simultaneous interventions and not a single intervention. The main mechanisms of noise generation and the related transmission lines are depicted in Figure 1.

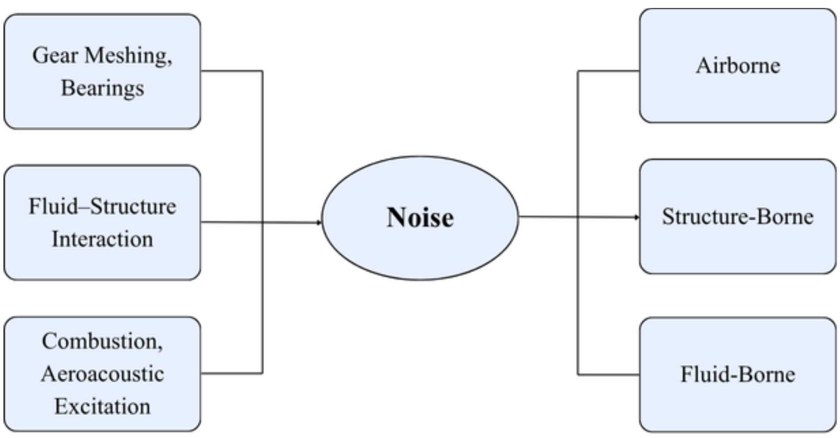

Figure 1. Schematic representation of mechanical noise sources and their propagation pathways.

2.3 Traditional Noise Control Limitations

Traditional methods of noise control in mechanical systems have been dependent on passive methods of noise control, which include barriers, absorbers, and damping materials. Despite the fact that these approaches have been well established, they do have limitations associated with them. Passive systems come with specific requirements of mass or thickness to get pertinent attenuation, which contradicts the modern engineering requirements of lightweight and compact designs (Gonzalez, 2022). Besides, passive treatments perform best in the mid-to-high-frequency spectrum and usually provide minimal performance in broad bandwidths.

Such limitations have prompted the desire to look at more flexible and multifunctional approaches. Active noise control, smart materials, and engineered structures (including topological acoustic systems) have become some of the promising alternatives, which can help solve both the broadband and low-frequency noise issues (Ma et al., 2019). The reason why these sophisticated solutions are necessary is part of the general trend of addressing the deficiencies of traditional passive treatments by using material science and dynamic control technologies. Table 1 depicts a summary of widespread mechanical noise origins, the processes that govern them, and the predominant propagation routes.

Table 1. Noise Sources, Mechanisms, and Propagation Characteristics

Noise Source	Primary Mechanism	Dominant Frequency	Propagation Path	Applications
Gear trains	Meshing impacts, stiffness variation	Mid–high	Structure-borne	Automotive, robotics
Bearings	Surface excitation, lubrication effects	Mid	Structure-borne	Rotating machinery
EV motors	Electromagnetic/inverter noise	High	Airborne	Electric vehicles
Turbomachinery	Turbulence, blade-passing	Mid–high	Airborne	Aerospace, HVAC
Hydraulic systems	Pressure pulsation, cavitation	Low–mid	Fluid-borne	Industrial equipment

3. Passive Noise Reduction Techniques

3.1 Advanced Damping Materials

Passive damping materials are a basis of approach to the minimization of mechanical vibration and transmitted noise. The viscoelastic polymers are still one of the most popular solutions because of their capacity to absorb vibrational energy by internal molecular friction. Polymer chemistry, temperature-dependent behaviour, and hybrid layering allow their performance to be customised to meet the needs of structural applications that require flexibility and durability. During the last few years, nanocomposites have become a new sophisticated category of damping media. Adding nanoparticles, e.g., silica, carbon nanotubes, or derivatives of graphene, leads to an increase in stiffness, damping coefficient, and thermal stability to allow optimal vibration dissipation without the use of a large amount of material (Vašina, 2022).

Another significant innovation is constrained-layer damping systems, in which a viscoelastic core is enclosed between hard outer layers in order to enhance shear deformation and energy loss. These structures have tremendous benefits over conventional unconstrained polymers, particularly plate-like constituents in the automotive, aerospace, and industrial machinery. Also, computational optimization tools have facilitated constrained-layer designs to optimize the thickness of the layers and the choice of the material that yields maximum noise attenuation (Kelemenová et al., 2020).

3.2 Vibration Isolation and Decoupling Strategies

The techniques of vibration isolation target the minimization of the spread of vibrational energy of a source through the supporting structure. Elastomeric mounts are typically adopted because they offer a combination of flexibility and damping and are made of compounds like natural or synthetic elastomers. Their frequency-tuning feature enables them to be customized to use with machinery with definite operation ranges, which provides stable isolation and a long service life (Zhang et al., 2022).

Another useful passive method is tuned mass dampers (TMDs) that provide a secondary mass spring system, which is tuned to oppose the predominant vibration frequencies. TMDS finds application mostly in large structural parts or precision machinery where resonance control is a key factor. Hybrid isolators, which combine mechanical springs with damping layers or nonlinear restoring elements, broaden the design space by providing wider bandwidth isolation and the ability to work with multi-degree-of-freedom systems. The stability and noise mitigation in more complicated vibration environments contribute further to the development of decoupling strategies for a redundant or parallel platform (Zhang et al., 2022).

3.3 Acoustic Insulation and Absorption Technologies

Acoustic insulation materials have the objective of resisting the passage of sound, whereas absorptive materials are employed to reduce acoustic transmission and convert acoustic energy into heat by frictional and viscous processes. Porous materials, including foams, fibrous mats, and granular composites, are still key to passive noise absorption owing to their capacity to dampen mid- to high-frequency sound. Some of the latest innovations are the construction of sound-absorbing concretes, which either recycle aggregates or lightweight fillers or use porous structures to improve acoustic behavior without compromising structural integrity (Amran et al., 2021).

Architected porous structures and meta-fibers enhance tunability in absorption behavior, providing better performance in desirable frequency bands. Additive manufacturing has also increased the potential through complex internal geometries, like graded porosity, channel networks, or resonant cavities, that cannot be made by other fabrication methods. These printed frameworks promote sound absorption at low volumes of materials, which is consistent with the current design demands of lightweight and effective noise control (Vašina, 2022).

3.4 Emerging Passive Solutions

Mechanical metamaterials are a promising development in passive noise reduction because of the periodic structures that have been engineered, which are able to generate band gaps -frequency bands in which the propagation of waves is suppressed. Such materials can attain attenuation on the scale of subwavelength attenuation and succeed in low-frequency noise, which would otherwise pose a challenge to passive control techniques (Noguchi et al., 2023). Their designs are frequently based upon the following ideas: local resonance, labyrinthine pathway, and topological design that change the wave propagation using constructive interference.

Topology-optimized acoustic barriers are extensions of these ideas, applied based on mathematical optimization to define the best allocation of material in a structure to attain maximum attenuation. These systems are able to provide high-performance sound blocking with less thickness and mass and can be used in aerospace, transportation, and building acoustics in areas where space and weight are of great concern. The development of computing technologies and the creation of materials has made rapid progress in the implementation of such advanced barrier designs (Noguchi et al., 2023) possible.

4. Active Noise Control (ANC) Technologies

4.1 Principles and Control Algorithms

Active Noise Control (ANC) is based on the principle of the production of an anti-noise signal that destructively interferes with the undesired sound. The current ANC systems are based on adaptive signal-processing algorithms that can adapt in real time to changes in the characteristics of noise. Figure 2 gives a high-level breakdown of key noise-control strategies that are discussed in this section.

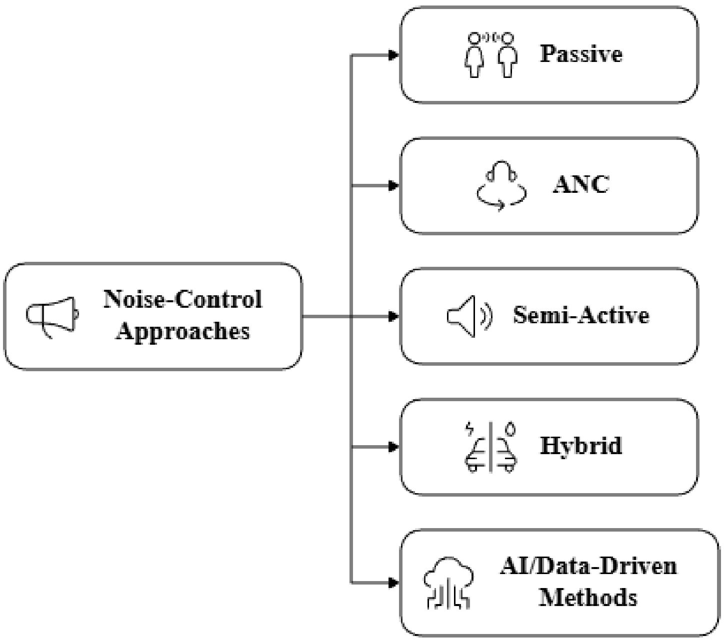

Figure 2. Classification of passive, active, semi-active, hybrid, and AI-driven noise-control approaches

The most basic of these is the Least Mean Squares (LMS) algorithm and its variants, as it is simple, robust, and has the ability to give consistent convergence in changing conditions (Shi et al., 2023). Of particular importance is the Filtered-x LMS (FxLMS) algorithm, which takes into consideration the second path, which is the dynamics between the controller, actuator, and the error sensor in the adaptation process. This renders FxLMS the most common algorithm used in work ANC systems (Yang et al., 2018). Figure 3 illustrates the operational flow of an adaptive active noise-control system realized with the help of LMS/FxLMS algorithms.

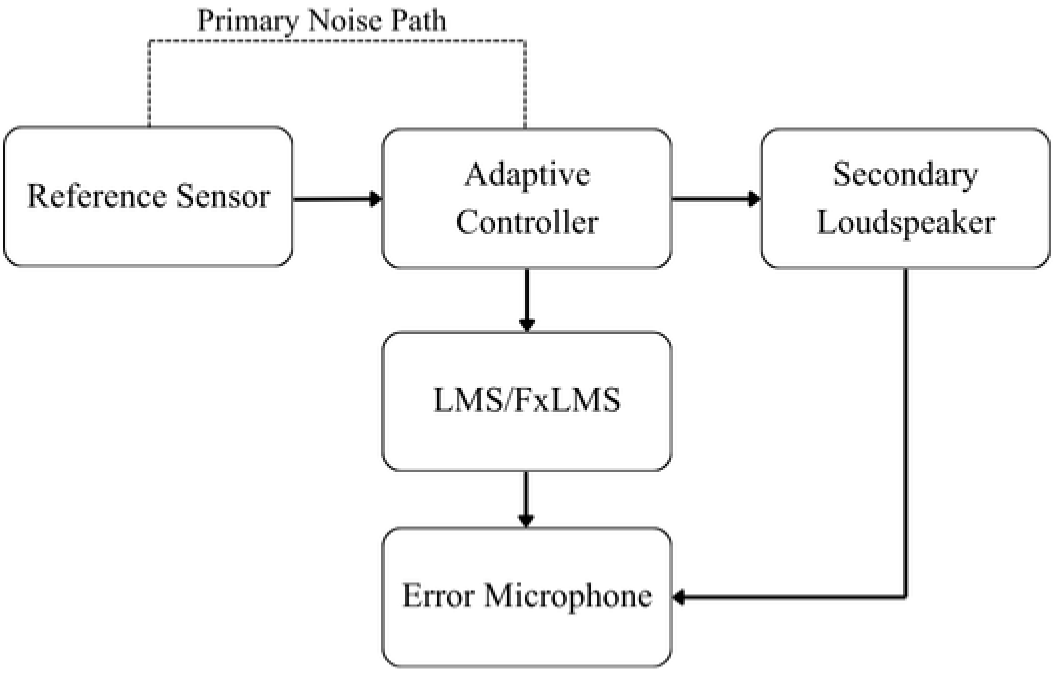

Figure 3. Block diagram of an adaptive active noise-control system using the LMS/FxLMS algorithm.

Adaptive filtering schemes may be based on the feedforward or the feedback control scheme. Feedforward ANC works well when reference information concerning the primary noise is accessible so that proactive cancellation can be done. Unpredictable noise is better suited to feedback control, which has more stringent stability requirements. The developments in frequency-domain implementation have also enhanced computational efficiency and convergence rates, enabling high-performance ANC in complicated mechanical conditions (Yang et al., 2018).

4.2 Applications in Mechanical Systems

ANC has found extensive use in mechanical systems in which traditional passive treatments are no longer practical, especially at low frequencies. ANC also overcomes low-frequency engine harmonics in engine cabins to enhance the acoustic comfort without adding any weight-intensive materials (Chawla and Gill, 2024). ANC also can be used in ducts and HVAC systems to reduce tonal and broadband noise related to turbulence in airflows and mechanical vibrations to operate at a lower noise level in residential and industrial locations. ANC methods used in rotating machinery reduce periodic noises and vibrations caused by asymmetries or blade passages or aerodynamic excitation. Multi-channel controllers make it possible to control the more complicated fields of spatial noise, enhancing the attenuation of huge machinery houses (Shi et al., 2023). These applications illustrate the improvement in acoustic performance by ANC in the cases where passive solutions can be physically/structurally prohibited.

4.3 Innovative Implementations

The recent trends have moved towards distributed and cooperative ANC structures. Distributed ANC arrays A number of spatially distributed sensors and actuators are coordinated by networked algorithms. These systems improve strength and coverage, especially of acoustic space that is large or of irregular shape (Dong et al., 2021).

Decentralized control strategies whereby the acoustic space is partitioned into self-controlled regions have been popular because of their modular property and less computational load. Such systems enhance fault tolerance and scalability, which is why they can be designed to meet the needs of multi-node mechanical systems, including expanded hvac ducts or car interiors (Dong et al., 2021). Also, new wireless ANC nodes minimize the use of complicated wiring, provide flexibility in deployment, and can more easily fit into the new industrial landscapes (Shi et al., 2023).

4.4 Challenges and Future Prospects

Nevertheless, ANC has significant challenges that affect design and implementation despite its promise. The power consumption is still an issue in the case of portable or embedded systems, in particular, the systems that need to work continuously or have multi-channel layouts (Tang et al., 2023). The problem of stability is also a major issue especially in feedback ANC where modeling errors or environmental variations may lead to poor performance. One of the aspects of stable adaptation under diverse operating conditions is the necessity to ensure that the advanced algorithms are able to perform robust updates in their needed parameters.

The other common restriction is frequency range since ANC works better at low frequencies when passive materials are least effective. The effectiveness of ANC decreases in higher-frequency frequencies as wavelengths and spatial variation in sound fields increase (Chawla and Gill, 2024). Stability-guaranteed algorithms, energy-efficient architectures, and hybrid systems that incorporate ANC with smart materials are likely to be studied in the future in order to expand the scope of operations and increase the long-term self-sustainability of the systems (Tang et al., 2023).

5. Semi-Active and Hybrid Noise Control Approaches

5.1 Magnetorheological (MR) and Electrorheological (ER) Solutions

Semi-active control systems take advantage of field-responsive materials, including magnetorheological (MR) and electrorheological (ER) fluids, to regulate their mechanical characteristics in real time. MR and ER fluids will exhibit a rapid and reversible viscosity effect in response to the magnetic or electric field, which allows adaptive vibration absorbers and mounts to react to different operation conditions (Kumar et al., 2019). The materials enhance damping with the benefit of varying damping properties without necessarily supplying constant high-power, unlike fully active systems.

This type of adaptive mount is especially useful with the varying loads or generalized excitation. Semi-active solutions offer a tradeoff between controllability and energy efficiency that enables the dynamic control of stiffness and damping ratios to better reduce the transmitted vibrations. Their high trustworthiness, swift reaction, and moderate energy needs facilitate MR- and ER-based systems to be considered in next-generation noise-control structures (Pawelczyk et al., 2022).

5.2 Piezoelectric and Smart-Material-Based Systems

Many smart noise-control systems are based on piezoelectric materials, which are capable of transducing mechanical strain and electrical charge and vice versa. Piezoelectric elements can either act as sensors, actuators, or combined transducers when installed in structures. Shunt damping is one of the most common techniques that ground piezoelectric patches on electrical circuitry, and the piezoelectric patches can be tuned to dissipate vibrational energy by tuning the electrical impedance to structural resonance modes (Nayak et al., 2025). This method gives good passive-like attenuation, and the benefit of tunability is acquired. Piezo-composites and smart panels also take these possibilities one step further with distributed piezoelectric elements embedded in structural layers. These multifunctional composites are more rigid, adjustable, and real real-time structural monitoring. They can be incorporated into the aerospace, automobile, and machinery components without causing excessive mass penalties due to their light weight (Nayak et al., 2025). Investigations into piezoelectric systems would enhance their stability and performance when used with semi-active control logic to allow the piezoelectric to adapt autonomously to different vibration modes and sources of noise.

5.3 Hybrid Passive–Active Techniques

Hybrid noise-control methods combine passive, like damping layers or acoustic insulation, with active or semi-active systems in order to obtain a wider range of bandwidth attenuation. Intelligent structures are a major trend in hybrid design, which employs sensors, actuators, as well as embedded control algorithms, in the frame of a structured design. The systems increase vibration damping by incorporating both passive properties and passive characteristics that can be actively controlled (Wrona et al., 2022).

The other emerging innovation here is multifunctional acoustic panels that have both structural load-bearing capacity and passive absorption and active noise cancellation. They also enable their layered architectures to place passive materials and active actuators or semi-active devices strategically to enhance low-frequency operation where passive approaches fail to work (Murao et al., 2019). Those hybrid solutions are more flexible and stronger and can assist in filling the area between the old noise-control techniques and the new performance needs.

6. Noise Reduction Through Advanced Material Engineering

6.1 Acoustic Metamaterials

The use of acoustic metamaterials has become one of the most disruptive inventions in noise-control engineering because they can control the propagation of waves based on engineered microstructures and not the conventional bulk properties. Such materials may attain negative effective density or negative modulus, and, therefore, it is possible to create acoustic band gaps in which sound transmission is inhibited between chosen frequency ranges (Zhang et al., 2023). These bandgap-design techniques can achieve attenuation of low-frequency noise, which is generally poorly attenuated in conventional passive materials.

Another important development brought about by the idea of metamaterial design is lightweight but high-performance acoustic barriers. The more intricate designs, like coiled channels, resonant cavities, or labyrinthine designs, provide a longer acoustic interaction range without extra mass addition. These composite structures have many use cases in reducing noise by a significant margin and achieving high weight requirements in the automotive and aerospace engineering industries (Zhang et al., 2023). The incorporation into mechanical systems and the way they are tailored geometrically can eliminate long-standing deficiencies of density-based acoustic solutions.

6.2 Nanostructured Materials

Nanostructured materials have superior damping and vibration-control properties due to the interaction of the nanoscale that is not available with traditional composites. It is demonstrated that graphene-based nanocomposites, such as those, have exceptional damping behavior attributed to the high specific surface area of graphene, high interfacial bonding, and the confinement of polymer chain movement. Graphene flakes have been demonstrated to be susceptible to the size and shape, which can be used to greatly control the amount of energy dissipated to better tune the damping properties to noise-controlling purposes (Sarikaya et al., 2020).

Likewise, the reinforced composite of carbon nanotube (CNT) makes significant contributions to strengthening, stiffness, and viscoelastic characteristics. NTs also improve structural stability and vibrational absorption, which means that these materials can be used in decreasing noise levels in electric cars, aerospace parts, and rotating machines (Gan et al., 2018). Nanostructured materials can be designed to perform better in multifunctional operations by adjusting the dispersion, orientation, and compatibility of the matrix.

6.3 Additive Manufacturing for Acoustic Optimization

Additive manufacturing (AM) has changed how acoustic structures are made, as it allows complex geometries that were formerly challenging to make. With the aid of methods, including material extrusion, laser sintering, and stereolithography, engineers are able to develop lattice structures, graded materials, and multifunctional components that are able to maximize sound absorption and transmission control. The frequency-specific customization and accurate control of porosity, stiffness gradients, and resonant behavior are facilitated by these structured materials (Suaraz and del Mar Espinosa, 2020).

The recent advances in AM have seen it being applied to load-carrying acoustic panels, especially in aerospace environments where structural performance and reduction of noise had to co-exist. Additive manufacturing has enabled the production of multifunctional sandwich panels that incorporate lightweight cores, resonant cavities, and viscoelastic layers in a single structure to offer acoustic attenuation and mechanical strength (Pierre et al., 2023). These innovations demonstrate the increased contribution of AM to the integration of structural and acoustic design, which allows the highly optimized solutions of the next-generation mechanical systems. In conclusion of new trends in noise reduction based on materials, Table 2 will list the important advanced materials along with their preeminent acoustic processes.

Table 2. Advanced Acoustic Materials and Their Mechanisms

Material Type	Dominant Mechanism	Mass/Stiffness Profile	Target Frequencies	Integration Level
Viscoelastic nanocomposites	Internal damping	Light, tunable	Mid–high	Layers/coatings
Constrained-layer systems	Shear dissipation	Moderate stiffness	Mid	Structural panels
Acoustic metamaterials	Local resonance, band gaps	Very light	Low–mid	Built-in cores
Graphene/CNT composites	Interfacial damping	Ultra-light	Broad	Embedded matrices
AM lattice structures	Porosity/impedance tuning	Ultra-light	Mid–high	Acoustic cores

7. Algorithmic, Data-Driven, and AI-Enhanced Noise Reduction

7.1 AI/ML for Noise Prediction and Control

Machine learning (ML) and artificial intelligence (AI) have become a pervasive part of contemporary noise-control engineering, and are able to deliver data-driven features that are not limited by traditional analytical or adaptive algorithms. Learning intricate nonlinear feedback between the noise sources, the control signals, and the system responses, the neural networks have shown high promise in Active Noise Control (ANC). Their capability to forecast the noise behavior in dynamic settings facilitates a stronger cancellation, particularly when the conventional adaptive filters fail because of the nonstationary or broadband noise trends (Olodu, n.d.).

The application of AI has also positively affected the implementation of model-predictive control structures, as the prediction accuracy is improved, and the possibility of noise reduction through the application of ML algorithms is possible. Monitoring systems driven by AI in the context of transportation and smart cities can be used to continuously evaluate the level of noise and identify problematic trends in time, helping in the optimization of control mechanisms of mechanical and rail systems (Havran and Orynchak, 2024). The above developments show that AI will enable noise prediction to be more proactive rather than reactive to improve the overall reliability of the system.

7.2 Digital Twinning for Acoustic Simulations

Digital twinning is bringing a new paradigm to the subject of acoustic simulation by enabling a high-fidelity virtual twin of a physical system. Noise generation, propagation, and structural interactions can also be modeled digitally, and engineers could test the changes before the physical implementation. Digital twins are also increasingly assisted by the integration of sophisticated noise-monitoring and data-acquisition technologies, in which real-time acoustic sensorimeters, like those shown in noise-monitoring prototypes in society, give feedback to ensure that precise and adaptive virtual acoustic proxies are maintained (Quintero et al., 2023).

In the case of noise control applications, real-time monitoring and adjustment of the acoustic conditions can be realized with digital twins. By routinely updating itself with information from sensors, a digital twin can detect departures from expected noise behavior and assist with adaptive strategies to mitigate noise. Digital twinning is an important technology in the next generation of mechanical systems because virtual prototyping lowers development expenses and shortens the time to design an optimized structure for noise control.

7.3 Optimization Algorithms

The optimization techniques are important in the design of acoustically efficient mechanical parts. Swarm-intelligence-based algorithms like particle swarm optimization (PSO) and genetic algorithms have strong search capabilities for the complex acoustic design problems. PSO is a collective behavior-inspired algorithm with minimal complexity, convergence, and flexibility to multi-objective optimization problems and is popular because of these characteristics (Wang et al., 2018).

The algorithms are used to optimize geometry, material distribution, and system parameters to improve the design of acoustic barriers, vibration isolators, and resonant structures. Swarm intelligence has been applied in the field of acoustic defect detection to improve the detection of features to make diagnostic evaluations more accurate and fast (Zhang et al., 2018). Combining these calculation techniques with the current noise-control technologies, an engineer is able to create more sophisticated and effective solutions to the problem of noise.

8. Application-Specific Innovations

8.1 Automotive Systems

The concept of noise control in automotive engineering has also changed dramatically as the concept of electric vehicles (EVs) emerges. Although EVs remove the noise of combustion, they create additional acoustic problems like high frequency inverter noise, tyre-road interaction and structure-borne vibrations that are noticeable in lower noise cabins (O'Boy et al., 2024). Mitigation efforts now focus on active damping techniques in which sensors and actuators modulate vibrational responses in real time to reduce tonal and broadband noise.

In addition, engine-bay and underbody acoustic materials have been redesigned to cover EV-specific frequencies and lightweighting needs. Specialized absorbers, structural foams, and composite barriers are being added in order to make sure that there is comfort with no interruption of vehicle efficiency. A combination of sophisticated materials and active control structures is an all-encompassing solution to automotive noise control (O'Boy et al., 2024).

8.2 Aerospace and Turbomachinery

Noise control is of paramount importance in the field of aerospace and turbomachinery due to its environmental compliance, comfort in the cabin, and aerodynamics. One of the tools that have emerged in the recent past is aeroacoustic shaping; the act of changing surface geometry to control noise caused by the flow. Bionic or bio-inspired modifications to the leading edge of blades have resulted in measurable performance improvements, both in terms of reduced noise and enhanced aerodynamic efficiency, indicating the value of natural patterns in the design of high-performance blades (Liu et al., 2021).

In other developments, there are linear technologies, in which sound-absorptive engineered surfaces within nacelles or ducts absorb sound over wide frequency bands. These liners, in combination with optimized blade geometry, help to mitigate tonal peaks and wake-blade interactions typical in the operation of turbomachinery. These directions show an overlap between materials engineering, bio-inspiration design, and optimization by the computer (Liu et al., 2021).

8.3 Industrial Machinery and Manufacturing

The industrial noise reduction aims at reducing noise at the tool level and the machine level. Low-noise tool design in machining has become pertinent towards ensuring safety to the operator and also enhancing precision. Acoustic emissions are highly dependent on the structural dynamics of cutting tools and tool holders; hence, to maximize the tool stiffness, geometry, and damping properties, sophisticated measurement methods and improved structural modeling have been employed (Lanz, 2021).

In addition to individual tools, complete machine frames have been redesigned with more dampening material as well as structural reinforcement. Sensors embedded and other measurement devices at the tool center point enable the real-time identification of the vibrational instabilities, and corrective measures can be implemented to minimize noise and still enhance the machining performance (Lanz, 2021). These combined solutions are indicative of the increased relevance of dynamic monitoring in noise management in manufacturing.

8.4 HVAC and Building Mechanical Systems

The contribution of heating, ventilation, and air-conditioning (HVAC) systems to the level of noise indoors has led to research on quieter airflow and mechanical parts. Conventional silencing systems like duct silencers are still useful, especially when tuned to low-frequency noise that forms the disturbance by fans and turbulence in airflow. Recent developments have led to silencers that are able to reduce low-frequency content using internal geometry designs that are well-calculated (Piana et al., 2022).

Intelligent diffusers and airflow control systems are also essential in the minimization of vortex shedding and noise caused by turbulence. The mechanical vibration transmission along buildings can be reduced by structural adjustments of the HVAC components and the use of better insulation materials. The holistic approach to designing noise management in the HVAC industry makes the interior of buildings less noisy and has minimal effects on the system efficiency (Awad and Omar, 2022).

9. Comparative Assessment of Techniques

9.1 Performance Benchmarks

The quality of noise-reduction strategies should be evaluated by a close comparison of such performance measures as frequency range, attenuation capability, and long-term durability. Techniques range considerably in their operational bandwidth: passive techniques are frequently good at mid- to high frequencies, and active noise control (ANC) is better at low frequencies for attenuation, where long wavelengths preclude the passive materials from being very efficient (Singh et al., 2024). Hybrid and data-driven systems use a combination of passive absorption and adaptive filtering or predictive algorithms to provide greater and more uniform attenuation.

Durability is another important benchmark, particularly in industrial and environmental applications where exposure to mechanical stress, temperature variation, and weathering can degrade performance over time. In other words, passive barriers, which are deployed in outdoor sound mitigation as in UAV or urban settings, should be able to sustain varying environmental conditions and produce uniform attenuation (Ivošević et al., 2021). The performance tests thus would involve not just the acoustic tests but life cycle durability tests to dictate the reliability over a long period.

9.2 Cost, Scalability, and Energy Considerations

The role of economic factors in the selection of adequate solutions against noise is significant. Passive materials can be cheaper to purchase and less energy-demanding, thus suitable to scale to large-scale use, but can need more material volume, thus restricting weight and installation limitations. In comparison, ANC and AI-enhanced systems can attain better performance using less material mass, but they need more energy, bigger and more complicated hardware, and continuous maintenance (Singh et al., 2024).

Also, the technology is determined by scalability. Passive systems have good scalability to environmental applications or infrastructure, whereas more sophisticated active or hybrid systems can be limited by cost, complexity of computation, and interoperability of the system. According to life-cycle analysis, innovative methods, such as engineered acoustic materials or hybrid mitigation structures, can be cost-effective in the case of long-term performance, maintenance-reduction, and efficiency (Garg, 2022). Manufacturability also has to be considered, and in particular, new structures whose construction could demand special procedures or new materials.

9.3 Environmental and Regulatory Compliance

The preventative measures on noise reduction should be consistent with regulatory frameworks and environmental policies to address the permissible levels of noise exposure. The design requirements of industrial systems and noise barriers in cities are guided by international standards, such as ISO noise guidelines. An essential measure of compliance is the choice of solutions based on the limits prescribed without surpassing material, cost, or energy restrictions (Kurra, 2020).

The issue of sustainability has been growing more pivotal. To lessen environmental impact, green materials and noise-control technologies that are environmentally friendly are currently being focused on. The current trends in eco-friendly passive buildings and novel attenuation walls contribute to the preservation of the environment and offer adequate acoustic response (Zanganeh et al., 2024). On the same note, the larger environmental management policies demand the whole-room approach to noise-reduction activities that incorporate long-term environmental sustainability, safeguarding the population, and safeguarding the health of people (Garg, 2022). Table 3 will provide a comparative preview of the key noise-control strategies, their working nature, and their general applications.

Table 3. Comparative Overview of Major Noise-Control Strategies

Technique Class	Key Principle	Effective Frequency Range	Energy Demand	Applications
Passive	Absorption, damping	Mid–high	Very low	HVAC, housings
ANC	Anti-noise generation	Low	Moderate–high	EV cabins, ducts
Semi-active	Variable stiffness/damping	Low–mid	Low–moderate	Mounts, frames
Hybrid	Passive–active synergy	Wide	Moderate	Aerospace panels
AI-based	Predictive control	Adaptive	Moderate	Smart machinery

10. Research Gaps and Future Directions

10.1 Integration of Smart Materials and AI

The mechanical noise-control systems of the future require a single adaptive architecture combining smart materials and control on the level of AI. One of the research gaps is to develop real-time, multi-physics models that are fully coupled between structural mechanics, electromechanical behavior, and acoustic fields, such that sensing, prediction, and actuation are one system. Smart buildings need to bridge the gap between sensors, AI inference, and intelligent actuators to allow dynamic response to changes in noise patterns by changing their stiffness, damping, or impedance. Little has been done in terms of the mechanistic understanding of the way AI reforms modal energy routes, and the challenge of stability, transparency, and reliability of learning based controllers on embedded hardware is not resolved yet.

10.2 Multi-Functional Acoustic Systems

The next generation acoustic materials need to integrate noise reduction capabilities with structural and energy needs, and come up with light-weight systems that absorb sound, provide structural support, and they may utilize the vibrational energy. The simultaneous attainment of these multiple functions presents trade-offs, with the trade-off between stiffness and damping being larger, and localized weaknesses being introduced by the presence of piezoelectric or porous phases. Mechanistically, the answer is found in hierarchical designs that give damping on nanoscale dimensions, impedance tuning on microscale designs, and mechanical loads on mesoscale designs. The knowledge of long-term sustainability, especially in terms of flexibility, bending, and other thermally strained acoustic elements, is critical to the implementation of these multi-purpose systems into actual settings.

10.3 Cross-Disciplinary Opportunities

It is possible to note the considerable breakthroughs with cross-disciplinary approaches (e.g., bio-inspired noise control and micro-structured surfaces). Biological analogues exhibit mechanisms such as vortex disruption, pressure-gradient smoothing, and distributed micro-resonances, which can be replicated as mechanical components to cut down on noise generated by flows. Likewise, micro-textured surfaces with ribs, holes, or subwavelength channels will also alter the behavior of the boundary layers and form local resonances, which will damp particular frequencies. Nevertheless, predictive design is a significant gap, because to connect microscopic geometric structures to the acoustic performance of the entire system in turbulent and multi-directional flows, there is a need to utilize unified modelling methods of acoustics with CFD and microfabrication expertise.

10.4 Outlook for Next-Generation Systems

Mechanical noise control will take a new path in the future, rather than isolated treatment of acoustic-mechanical-electrical fully integrated systems. These new generation solutions will be physics-informed AI-based, smart materials, and digital twins to dynamically respond to the dynamically changing look of operations, re-tune modal characteristics, redirect vibrational energy to benign channels, and counter aging or structural deterioration. Instead of just concentrating on attenuation, the new systems will aim at being adaptable, sustainable, robust, and with embedded intelligence. The vision will need combined advancements in material science, control theory, AI, and complex manufacturing to make noise control a design principle, not a retrofit solution.

11. Conclusion

The development of materials engineering, signal processing, and intelligent control has changed the nature of noise-reduction technologies, where a single technology was several isolated passive strategies to a combined adaptive system that can handle the complexity of the modern mechanical environment. According to this review, the advancement has been facilitated by a better mechanistic study of noise generation and propagation, alongside the introduction of novel metamaterials, intelligent damping media, hybrid control systems, and AI-accompanied predictive capabilities. However, there are still huge opportunities. Interdisciplinary cooperation and cohesive design practices will be essential to achieve a smooth integration of smart materials and data-driven controllers, create really multifunctional acoustic structures, and make use of bio-inspired and micro-structured designs. The noise-control systems of the future should be viewed as cyber-physical systems, which constantly sense, learn, and change with the emerging acoustic conditions. These systems will not only eliminate noise but will also redistribute vibrational energy, improve structural performance, and be a contributor towards a sustainability goal. With the shift of industries to machines that are lighter, quieter and smarter, the next generation noise-control technology will be a key factor in the maintenance of safety, environmental friendliness, and operational perfection of the entire mechanical processes.

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