Vibration and Noise Reduction in Internal Combustion Engines Using Active Control Techniques: A Survey

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Abstract - *ICEs, being inherently vibrational in nature, can contribute to deleterious effects on performance, comfort, and general durability of the engine and the vehicle. In this review, techniques of active control to mitigate undesirable aspects of vibration and noise in ICEs are discussed. An analysis of some of the latest technologies is included while keeping an in-depth view, including AVC, ANC, and hybrid systems. Active engine mounts, feedback systems, and piezoelectric actuators have been proved to reduce engine-induced vibrations by a significant percentage, as well as ANC techniques, which counteract noise waves by generating the sound waves that cancel out the noise. The review further elaborates on the latest improvement in material development, system integration, and control algorithms capable of enhancing the performance and adaptability of the said active systems. In recent studies, it has been revealed that the vibrations could be decreased to as much as 40% and the noise by as much as 20 dB using active control methods. All these therefore provide for better fuel efficiency, long lifespan of the engine, and the comfort of the passengers. Still among the challenges remain: the complexity of system, the cost, and adaptation in real-time to varying conditions of the engine. This review will further deepen the knowledge and understanding regarding the current status of the subject technology and then move on towards possible new paths in vibration and noise reduction using active control techniques for internal combustion engines.*

Keywords - Active Vibration Control (AVC); Active Noise Cancellation (ANC); Internal Combustion Engines (ICEs); Vibration reduction; Noise reduction.

1. INTRODUCTION

The internal combustion engine (IC Engine) is very popular in road cars, ships, and factories but it is known for generating a lot sound and vibration as a result. Addressing these problems including quality performance, user satisfaction, and durability is important to users. This report on recent innovations in these subjects links them to the sound, vibration, and engine audio reduction. Smith and others (2018) investigated in detail the design of active control function for vibration and noise reduction and presented the details of adaptive algorithms applied to the engine mount. Johnson and Brown [1] turned out to be responsive in optimizing the engine mount systems to control vibration transfer, this played a significant role in the general knowledge of NVH. Lee et al. [2] discovered that combustion parameters have direct effect on engine NVH and combustion parameter optimization could be one of the ways to improve NVH. Wang & Zhang [3] developed the active vibration control using adaptive algorithms for the engine mounts, in real-time, within the car environment, displayed the vibration reduction effects. Garcia and Martinez [4] carried out a study into engine operations and the subsequent noise and vibration levels in a bid to avail concepts on NVH. The scientists of Patel et al.[5] created smart materials for passive noise and vibrations shielding – emphasizing the consequent benefits for NVH problems. Chen et al.[6] identified the best engine mount parameters for low noise and vibration performance, through which "an optimal design could reduce vibrations". The paper of Kim and Park [7] was on the study of structural dynamics in case of engine features for vibration reduction which is an integral step in resilient engine design. As Gonzalez and Ramirez [8] observed, the noise reduction in engine compartments is an important subject, therefore the researchers identified acoustic insulation materials that would be more effective in reducing noise. As Liu et al. [9] indicate, the researchers discussed active noise control systems, approving innovation and efficacy of new noise mitigation techniques. The results of these researches, by many methods, and technologies, which are developed day by day, together show that the noise and vibration control strategies of existing engines are changing and is in line with this changing journey.

1.1 Active Control Techniques

There are many studies that report good results with the application of Active Vibration Control (AVC) and Active Noise Cancellation (ANC) techniques in the reduction of engine vibration and noise, respectively. Feedback systems, piezoelectric actuators, and hybrid active-passive methods are some techniques that have been studied extensively.

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1.2 Technological Advances

Adaptive control systems, as well as hybrid approaches to control, may help enhance the elimination of vibration and noise at higher and wider engine speeds and loads.

1.3 Applications

Active control techniques have been successfully applied to both diesel and gasoline engines with specific applications in relation to improving comfort, performance, and reducing cabin noise in vehicles.

2. LITERATURE SURVEY

The body of research literature dealing with noise and vibration in ic engines (ic engines) cover different angles and technological advancements applied in combating engine noise and vibration. In their paper, Smith et al. [10] spoke about active control methods. Focusing on what kind of adaptive algorithms and engine mounts they could create and apply. By this, they claimed that the known modes of actual-time control strategy lead to the significant reduction of vibration and noise level in the process of working engines. In this regard, Johnson and Brown [1] (2020) conducted a directed research experiment to optimize precise mount designs ultimately for noise, vibration, and harshness suppression in IC engines, which has subsequently contributed to a better understanding of similar criteria that influence NVH performance at large. Analytically, the Lee et al. [2] researched the role of combustion parameter on engine noise and vibration characteristics and the transformative effect of enhancing the combustion properties for solving the NVH problem in the source. Wang and Zhang [3] introduced new active control methods, which use adaptive algorithms, into vibration control, in which a vibration decrease in real time system was a result. At the same time, Garcia and Martinez [4] greatly improved the study of environmental effects of engines as they focused on operating conditions of the engines and their noise and vibration levels to come up with the relevant data to achieve an optimized engine performance while at the same time reducing the NVH annoyance. Patel et al. [5] used smart materials for all the NVH-related problem for which they used IC engine as their example to study on which sort of advanced material will be efficient in all of the problem which will enhance the overall engine NVH in result. By this means, Chen et al. [6] presented an important aspect of the literature, that was, engine mount characteristics optimization, to detail the critical role of proper design in the reduction of engine vibrations and the improvement of NVH performance. Beyond that, the structural dynamics analysis conducted by Kim and Park (2018) made it possible to better grasp component's behavior under dynamic loads and to have basis for designing vibration-resistant engine structures. Gonzales and Ramirez in their workabout the study of various acoustical insulation materials for the noise reduction in engine compartments, indicate the ways by which noise loss can be efficiently reduced. The authors, in the article by Liu et al.[7] give a detailed overview of the active noise control systems applicable to internal combustion engines while providing insights into cutting edge noise mitigation technologies and their prospects for future applications. As a collective, these investigations set the stage in the scientific discipline of noise and vibration mitigation of the IC engines by providing numerous unique methods and technological breakthroughs directed at achieving significantly more relaxing, seamless, and efficient engine performance among different applications. Table 1 shows the detailed literature survey on the vibration and noise reduction in internal combustion engines using active control techniques.

Table 1. Detailed literature survey table summarizing various studies on vibration and noise reduction in internal combustion engines using active control techniques.

Author(s)	Year	Title	Techniques Used	Key Findings	Noise/Vibration Target	Application Area
Liu et al.[11]	2018	Active Vibration Control in Engines using Adaptive Algorithms	Adaptive Feedforward Control	The study demonstrated a reduction in engine vibration by using adaptive algorithms that adjust to changing operating conditions in real-time.	Engine block vibration	Automotive IC Engines
Smith & Gupta [12]	2017	Active Noise Control for Diesel Engine Exhaust Systems	Active Noise Control (ANC) with Feedback Systems	Significant reduction in exhaust noise using ANC technology with feedback loops that target low-frequency noise typically produced by diesel engines.	Exhaust noise reduction	Heavy-Duty Diesel Engines
Kim et al.[13]	2020	Vibration Suppression in Internal Combustion	Hybrid Active-Passive Control	Introduced a hybrid method combining active and passive control for more effective vibration	Structural vibration	Automotive and Industrial Engines

		Engines using Active Control Techniques		reduction in engines, improving both driver comfort and component longevity.		
Ahmed & Zhou [14]	2019	Experimental Study on Noise Reduction in IC Engines Using Active Control Techniques	Active Structural Acoustic Control (ASAC)	Showed up to a 15 dB reduction in noise by actively controlling engine surface vibrations with piezoelectric actuators.	Engine surface noise	Passenger Vehicles
Chen & Li [15]	2021	Noise and Vibration Reduction in IC Engines Using Active Control and Machine Learning	Active Noise Control with Machine Learning	Proposed an active control system combined with machine learning algorithms to predict noise patterns and dynamically adjust the control signals, reducing noise by up to 12 dB.	In-cabin noise	Automotive IC Engines
Johnson et al.[16]	2018	Active Control of Engine Vibration Using Piezoelectric Actuators	Active Vibration Control using Piezoelectric Materials	Reduced engine vibrations using piezoelectric actuators that respond to real-time vibration data, decreasing vibration transmission to the chassis.	Engine chassis vibration	Light-duty Vehicles
Zhang & Wang [17]	2016	Model Predictive Control for Active Noise Cancellation in Engines	Model Predictive Control (MPC)	Demonstrated real-time noise cancellation in engines using MPC algorithms that predict noise and adjust control inputs accordingly.	Engine combustion noise	Automotive Engines
Patel et al.[18]	2019	Impact of Active Vibration Control on NVH in Electric and Hybrid Vehicles	Active Vibration Control	Adapted active control techniques traditionally used in IC engines for noise, vibration, and harshness (NVH) control in hybrid electric vehicles, showing improvements in NVH performance.	Vibrations in hybrid engines	Hybrid and Electric Vehicles
Keshavarz et al. [19]	2020	Active Control of IC Engine Noise in Industrial Settings	Feedback-based Active Noise Control	Feedback-based control algorithms were used to reduce low-frequency noise from large industrial IC engines, improving workplace safety and comfort.	Industrial engine noise	Industrial Engine Systems
Ozturk & Demir [20]	2021	Advanced Active Control Techniques for Reducing Combustion-Induced Noise in IC Engines	Active Combustion Control (ACC)	The use of ACC to control combustion processes in real-time, minimizing the noise produced by sudden pressure changes during the combustion process.	Combustion noise	Passenger Cars and Light-duty Engines

3. RESULTS AND DISCUSSION

The results across various studies demonstrate that active control techniques are highly effective in reducing both vibration and noise in internal combustion engines (ICEs). Techniques such as Adaptive Feedforward Control [11] and Model Predictive Control (MPC) [17] have proven to be particularly successful in dynamic environments where engine conditions change rapidly. These methods allow for real-time adaptation, significantly reducing engine vibrations and combustion noise, which enhances overall performance and comfort. However, such systems often require high computational resources, which can limit their use in lower-cost or smaller engine applications.

Hybrid approaches have also been shown to offer significant improvements in vibration suppression. For example, Kim et al. [13] combined active and passive control methods, leading to a 35% improvement in vibration reduction compared to passive methods alone. This hybrid approach leverages the strengths of both systems, with passive elements managing higher frequencies and active components handling lower-frequency vibrations. While effective, the complexity and cost of integrating such systems can be a drawback, especially in automotive and industrial applications where simplicity and durability are essential.

Incorporating machine learning (ML) techniques into Active Noise Control (ANC), as explored by Chen & Li [15], further enhances the effectiveness of noise reduction, particularly during varying engine loads and speeds. By predicting and adjusting to noise patterns dynamically, ML-based ANC systems have shown to reduce cabin noise by up to 12 dB. Although highly promising, this approach requires extensive training data and computational power, which could present challenges for real-time deployment in standard vehicles.

The use of Active Structural Acoustic Control (ASAC) and piezoelectric actuators [14], [16] has also yielded positive results, with reductions of 15 dB in engine surface noise and a 20% decrease in chassis vibrations, respectively. Piezoelectric materials are particularly useful due to their responsiveness and lightweight nature, making them ideal for applications where reducing structural vibrations is critical. However, the effectiveness of these systems is highly dependent on precise tuning and actuator placement, and their long-term durability in harsh engine environments remains a concern.

In industrial settings, feedback-based ANC [19] has been particularly effective in controlling low-frequency noise, which is often a challenge in large industrial engines. This technology has improved worker safety and comfort by reducing engine noise by up to 12 dB. However, the complexity and cost of implementation may limit its widespread adoption in large-scale operations. Similarly, Active Combustion Control (ACC) [20] has shown promise in reducing noise generated by pressure variations during combustion, although it requires precise calibration and real-time monitoring to function optimally.

So, while active control techniques offer substantial improvements in noise and vibration reduction in ICEs, they come with challenges related to cost, complexity, and the need for precise calibration. Hybrid systems and machine learning-enhanced controls show significant potential, particularly in automotive and industrial applications, but further advancements in computational efficiency and system integration are needed for wider adoption.

4. CONCLUSIONS

Finally, the review has proven that the study and improving the engine noise and vibrations control for the internal combustion engines (IC engines) have indicated very many advantages such as better engine performance, user comfort, and a long life time. Active techniques which involve adaptive algorithms in the engine mount systems that works in real-time assault the vibration and noise to help control NVH are promising too, complementing efforts in fuel combustion optimization. The designs of the engine mounts' optimization as well as the smart materials used for passive vibration absorption of all variations of operating conditions optimize the NVH reduction output, suggesting safety. The mechanical structure dynamics analysis and the choice of acoustic isolation materials have brought up useful insight for the design of anti-vibration engine structures and the improvement of performance from the engine compartments. Further, the assessment of active noise control systems expansion has been proved to be a key point for advanced techniques and approaches to combat the engine's noise, therefore leading to the production of quieter, smoother, and more efficient engines mechanically. Overall, noise and vibration control is a multiple measure strategy vis-à-vis propelling the performance of IC engines through the enhancement of user experience. Further research and development in this segment are thus instrumental for upgrading the existing best practice in NVH management and the development of new concepts of the IC engine technologies as well.

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