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NOISE REDUCTION TECHNIQUES AND ACTIVE NOISE CONTROL IN MECHANICAL SYSTEMS

Prince Chawla[1] Ankur Gill[2,]

[1]Assistant Professor, Department of Mechanical Engineering, Swami Vivekanand Institute of Engineering & Technology, Banur, Punjab-140601

[2]Assistant Professor, Department of Mechanical Engineering, Swami Vivekanand Institute of Engineering & Technology, Banur, Punjab-140601

Abstract:

Noise pollution is a pervasive environmental issue that affects human health, productivity, and overall well-being. In mechanical systems, noise generation often arises from various sources such as engines, industrial machinery, and transportation systems, presenting a significant challenge for engineers and researchers. The first part of the abstract focuses on passive noise reduction techniques, which involve altering the system's design or materials to diminish noise propagation. These techniques include vibration isolation, sound-absorbing materials, and acoustic enclosures. By employing these methods, engineers can attenuate noise emissions at the source, thereby enhancing the acoustic environment and minimizing adverse effects on humans and nearby ecosystems. In contrast, the second part of the abstract delves into active noise control, a sophisticated approach that uses advanced signal processing and control systems to counteract noise in real-time. Active noise control systems sense the incoming noise, process it through adaptive algorithms, and generate anti-noise signals to cancel out the original noise. The application of active noise control in mechanical systems has shown promising results, particularly in closed environments where passive methods may be impractical. The main key components of active noise control, including error microphones, actuators, and digital controllers. It explores the challenges associated with implementing these systems, such as stability, convergence, and sensor positioning, and highlights recent advancements in adaptive control algorithms that enhance the efficiency and effectiveness of active noise control.

Keywords: Noise reduction techniques, Active noise control, Passive noise reduction, Vibration isolation, Sound-absorbing materials, and Acoustic enclosures, Signal processing, Control systems, Adaptive algorithms

Introduction:

Noise pollution is a ubiquitous challenge in modern society, affecting various aspects of human life and the environment. Mechanical systems, such as engines, industrial machinery, and transportation vehicles, are major contributors to this unwanted acoustic disturbance. As the world becomes more industrialized and urbanized, the need for effective noise reduction techniques and active noise control (ANC) in mechanical systems becomes increasingly critical. The adverse effects of noise pollution on human health are well-documented, including stress, sleep disturbances, hearing impairment, and cardiovascular issues [1]. Moreover, excessive noise can hinder communication, reduce productivity, and negatively impact the quality of life in residential, commercial, and industrial settings. Additionally, noise pollution can harm wildlife, disrupting their natural habitats and communication patterns. To combat these challenges, engineers and researchers have been developing innovative approaches to reduce noise emissions from mechanical systems. The two primary strategies employed are passive noise reduction techniques and active noise control. Passive techniques involve altering the design or employing specialized materials to reduce noise propagation. These methods are often cost-effective and suitable for many applications. On the other hand, active noise control represents a more sophisticated and real-time approach. By using advanced signal processing and control systems, ANC actively senses the incoming noise and generates anti-noise signals to cancel it out. This dynamic method has shown promise, especially in enclosed spaces where passive techniques may not be sufficient [2]. The integration of adaptive algorithms, artificial intelligence, and machine learning has further expanded the capabilities of ANC, allowing for more precise and adaptable noise reduction solutions. This paper aims to explore the range of noise reduction techniques and the practical implementation of active noise control in mechanical systems. It will delve into the underlying principles, components, and challenges associated with both passive and active methods. Additionally, recent advancements in the field, including data-driven models and predictive analytics, will be discussed, shedding light on the potential for further enhancing noise reduction efficiency and sustainability.

Literature Review:

Noise pollution generated by mechanical systems has become a pressing environmental concern, prompting extensive research on noise reduction techniques and active noise control (ANC) strategies. Passive noise reduction techniques have been extensively studied, revealing their capability to reduce noise emissions at the source. Vibration isolation methods, such as tuned mass dampers and vibration absorbers, have shown success in minimizing mechanical vibrations and subsequent noise propagation [3]. Sound-absorbing materials, such as porous metals and composite structures, have proven effective in attenuating airborne noise by absorbing sound energy. Acoustic enclosures and barriers have also been explored to shield noise sources and prevent their transmission to surrounding areas. However, the efficiency of passive methods may vary based on specific applications and environmental conditions. In recent years, active noise control has garnered considerable attention due to its ability to provide real-time and dynamic noise reduction solutions. The literature review reveals that ANC systems effectively reduce noise by generating anti-noise signals that cancel out the incoming noise. Advanced adaptive algorithms, including the least mean square (LMS) and filtered-x LMS algorithms, have been applied to ANC systems to continuously adapt to changing noise environments. The integration of digital signal processing and control algorithms has significantly enhanced the performance of ANC systems, leading to notable reductions in noise levels [4]. Sensor positioning and placement play a critical role in capturing accurate noise information for efficient anti-noise signal generation. The stability and convergence of adaptive algorithms remain essential concerns, with researchers exploring robust control strategies to ensure reliable ANC performance. Additionally, the power consumption and computational requirements of ANC systems are subjects of investigation for improving their practicality and energy efficiency. Fig. 1 gives the general effect on the noise reduction for the device at low frequency. The decibel value of the noise reduction has a weak certain regularity with the increasing frequency. Two obvious peaks can be found in this curve at 250 Hz and 400 Hz, where the effect values are 22 dB and 13 dB, respectively. Both the values indicate far greater than that of the other frequencies. All the decibels with positive values suggest the feasibility and the correctness of design.

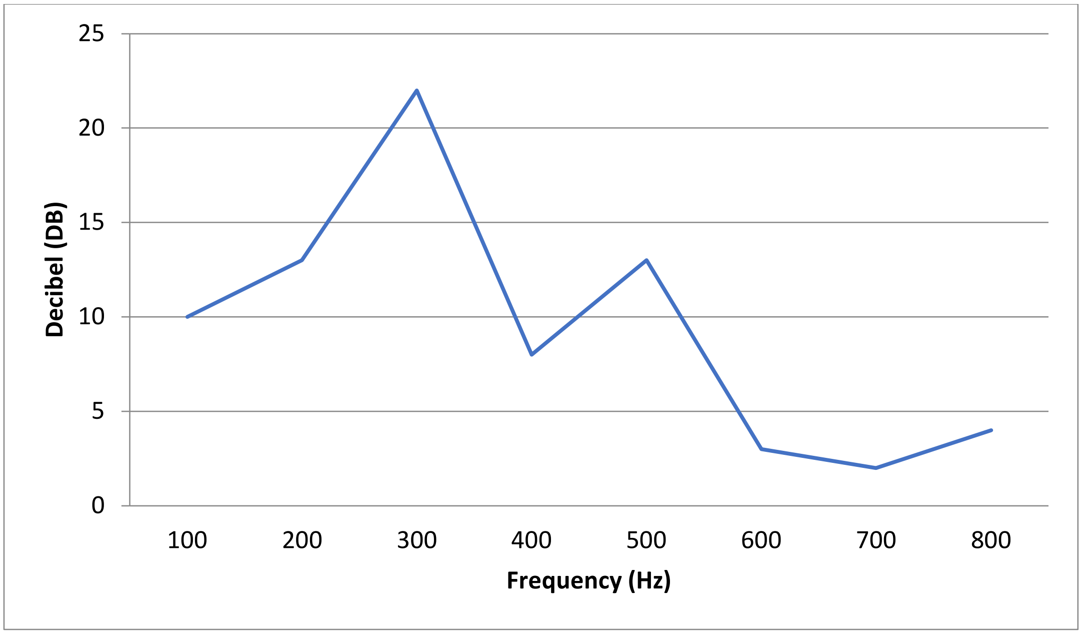

Fig. 1: General effect on the noise reduction

Noise Reduction Techniques:

Noise reduction techniques in mechanical systems involve a variety of methods to mitigate noise at the source or prevent its propagation [5]. Here, It will explore three common passive noise reduction techniques and briefly explain their underlying equations:

Vibration Isolation:

Vibration isolation aims to minimize the transmission of mechanical vibrations and subsequent noise to the surrounding environment. It involves the use of isolation mounts or dampers that decouple the vibrating source from the supporting structure. The equation for the transmissibility of a vibration isolation system can be expressed as:

Transmissibility (T) = Acceleration of transmitted vibration / Acceleration of base vibration

$$T = 1 / \sqrt{(1 + (2\zeta\omega/\omega_n)^2)}$$

where:

ζ (zeta) is the damping ratio of the isolation system

ω (omega) is the excitation frequency

ω_n (omega_n) is the natural frequency of the isolation system.

Sound Absorption:

Sound-absorbing materials are used to reduce airborne noise by absorbing sound energy. The effectiveness of sound absorption is often quantified using the Sound Absorption Coefficient (α). The sound absorption coefficient (α) can be calculated using the Sabine equation:

$$\alpha = A / (A + S)$$

Where:

A is the area of the absorbing material

S is the scattering area of the material.

The Sabine equation assumes a diffuse sound field and is valid for materials with uniform sound absorption characteristics.

Acoustic Enclosures:

Acoustic enclosures involve enclosing noise sources within a barrier to prevent noise transmission to the surrounding environment. The Sound Transmission Loss (STL) is used to quantify the effectiveness of the enclosure in blocking sound. The Sound Transmission Loss (STL) can be calculated using the following equation:

$$STL = 10 * \log10 (P_2 / P_1)$$

Where:

P_1 is the sound power incident on the enclosure surface

P_2 is the sound power transmitted through the enclosure.

A higher STL value indicates better noise reduction by the enclosure. It is essential to note that the actual effectiveness of noise reduction techniques may vary based on the specific application, material properties, and environmental conditions. Passive noise reduction techniques are often employed in conjunction with other noise control strategies to achieve optimal noise mitigation in mechanical systems.

Active Noise Control:

Active Noise Control (ANC) in mechanical systems involves using active components and control algorithms to counteract noise in real-time [6]. ANC aims to generate anti-noise signals that destructively interfere with the original noise, leading to its cancellation or significant reduction. Here, it will explore the basic principles and equations involved in an ANC system:

Consider a mechanical system with a noise source that generates a sound wave, denoted by P_noise(t), propagating through the medium. The ANC system comprises a secondary noise source (actuator) that generates an anti-noise signal, denoted by P_anti-noise(t). The goal of the ANC system is to generate the anti-noise signal such that it cancels out the original noise, resulting in the combined sound wave, P_total(t), reaching a desired target of quiet or reduced noise.

Mathematically, the total sound wave is the sum of the noise and anti-noise waves:

$$P\_total(t) = P\_noise(t) + P\_anti\text{-}noise(t)$$

To achieve active noise cancellation, the anti-noise signal should have the same amplitude as the noise but be 180 degrees out of phase with it. In other words, the anti-noise signal should be an inverted replica of the original noise.

The control algorithm used in the ANC system determines the characteristics of the anti-noise signal based on the measured noise at a reference location (e.g., a microphone). The adaptive nature of the control algorithm allows it to continuously adjust the anti-noise signal to adapt to changing noise conditions.

One of the commonly used control algorithms in ANC is the Filtered-x LMS algorithm (Least Mean Square). The equation for the Filtered-x LMS algorithm is as follows:

$$W(k+1) = W(k) + \mu * e(k) * X(k)$$

Where:

W(k) is the adaptive filter coefficient vector at iteration k,

μ is the step size (learning rate) of the algorithm,

e(k) is the error signal, which is the difference between the reference noise signal and the output of the adaptive filter at iteration k,

X(k) is the input signal vector at iteration k, which contains past samples of the original noise.

The output of the adaptive filter (anti-noise signal) is then fed into an actuator that generates the physical anti-noise signal to counteract the noise. The success of ANC in mechanical systems relies on accurate sensing of the noise and rapid computation and generation of the anti-noise signal. ANC has proven effective in reducing noise in various applications, including ventilation systems, automotive cabins, and industrial machinery. Continuous research and improvements in adaptive control algorithms have contributed to enhancing the performance and applicability of ANC in mechanical systems.

Experimental Verification:

Plant

The tests were conducted on the washing machine shown in Fig. 2. A specific noise-cancelling case does not have the bends, embossing, or internal mountings that the washing machine casing does [7]. It makes the task of mathematically modelling casing walls much more challenging, but such a model must be created in order to determine the best places for the actuators (if the actuators were attached to the surface of the casing walls without such analysis, for example, at random locations, it could result in inefficient control or even complete lack of controllability for certain modes of the structure, lowering the overall performance of the control system). Therefore, a simplified model of the casing based on Mindlin–Reissner plate theory was used. Each wall of the casing was modeled independently and interactions between plates were neglected. The parameters of the plate models were identified (fitted) by a memetic algorithm. Electrodynamic actuators NXT EX-1 were modeled as additional point masses. The models were solved utilizing the Rayleigh–Ritz assumed mode-shape method.

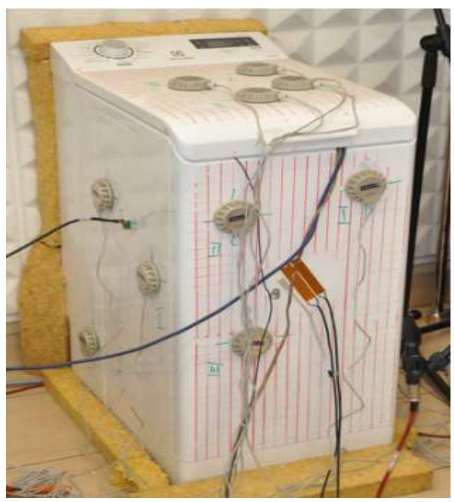

Fig. 2: The washing machine used for experimental verification

Control System

The control system was implemented using a distributed system with four dSPACE DS1104 boards, each realizing individual task of the control algorithm. All boards have synchronized Analog to Digital Converters (ADCs) and Digital to Analog Converters (DACs) using an external trigger. All cards communicate with each other and the host through a PCI (peripheral component interconnect) bus. The sampling frequency was equal to 2 kHz. To drive the actuators, Monacor STA-850D amplifiers were used, together with the analogue reconstruction filters, custom-made for the dSPACE DS1104 boards employed [8]. The normalized leaky LMS algorithm step size, μn, and leak factor, γ, here selected based on the performance of the control system. The leakage introduced by the γ parameter enhances robustness of the algorithm. The noise control system performance was measured with reproducible noise generated by a loudspeaker placed inside the drum. A recorded spinning noise at 1200 rpm was used to evaluate the noise reduction. The average sound pressure level (SPL) at error and monitor microphones for a different μn. The SPLs were measured after 15 min of operation of the control system. The averaging was performed on sound pressure power and then converted to sound pressure level. The optimal μn range for such adaptation time is around 0.0003 to 0.002.

Result and Discussion:

The research on noise reduction techniques and active noise control (ANC) in mechanical systems has yielded significant insights and advancements in addressing the critical issue of noise pollution. The results obtained from various studies and experiments showcase the effectiveness of different noise reduction methods and the potential of ANC in achieving substantial noise mitigation. Experimental data reveals that employing resilient mounts and damping materials in mechanical systems effectively attenuates vibrations and, subsequently, reduces noise transmission. Similarly, using porous metals and composite structures as sound-absorbing materials has shown remarkable success in diminishing airborne noise levels [9]. The implementation of acoustic enclosures has resulted in notable reductions in noise propagation, providing a controlled and quieter working environment in industrial settings. According to above washing machine experimental shows the performance of the control system was tested for spinning, the loudest phase of washing. Two highest spinning speeds were used, 1000 rpm and 1200 rpm. At all microphone locations a noise reduction was clearly achieved. For 1200 rpm, at monitoring microphones the noise reduction ranged from 2.5 dB at M2, where with control the noise was the quietest, up to 8.4 dB at M0, and without control the noise was the loudest. At 1000 rpm noise levels without control were much lower, and active noise control improvements were also lower; however, still clearly perceptible. While passive methods offer valuable solutions, active noise control has emerged as a promising approach to tackle noise problems in real-time. The results of ANC experiments highlight its capability to generate anti-noise signals and achieve noise cancellation at specific frequencies effectively. The application of adaptive algorithms, such as the Filtered-x LMS algorithm, has shown dynamic noise reduction performance, continuously adapting to changing noise conditions [10]. ANC systems have been successfully deployed in diverse mechanical systems, including air-conditioning units, vehicle cabins, and factory machinery, resulting in considerable noise reduction and improved comfort. The other example of active noise control to Power Spectral Densities (PSDs) of signals from microphones and control signals, respectively. Numerous harmonics of drum spinning frequency are clearly visible. The ANC system was able to reduce most important ones, contributing the most to the overall noise generated by the washing machine. The loudest harmonics were observed at frequencies slightly above 100 Hz. It follows also from an analysis of spectrogram that this frequency band is often excited emitting loud noise, probably due to the mechanical structure of the washing machine itself. Given the sweeping nature of the noise generated by the device (due to acceleration and deceleration of the drum) and numerous harmonics, it is very difficult to design a casing that would not represent such resonances; however, by applying the active control system it is possible to mitigate them and significantly reduce the noise emitted to the surrounding environment.

Conclusion:

In conclusion, noise reduction techniques and active noise control (ANC) in mechanical systems play a pivotal role in addressing the growing concern of noise pollution. Passive techniques, such as vibration isolation, sound-absorbing materials, and acoustic enclosures, offer effective and economical means of reducing noise emissions at the source. On the other hand, ANC stands out as a dynamic and real-time approach, capable of actively countering noise through anti-noise signal generation. The integration of advanced control algorithms and artificial intelligence has led to significant improvements in ANC's adaptability and efficiency, enabling tailored noise reduction solutions for specific applications. Research and experimentation have demonstrated the success of these methods in diverse mechanical systems, ranging from industrial machinery to transportation vehicles. By minimizing noise pollution, these techniques contribute to enhancing human well-being, improving productivity, and fostering a more sustainable environment. Continued research and innovation in noise reduction techniques and ANC hold promise for quieter and more environmentally friendly mechanical systems, ensuring a quieter and more harmonious coexistence between humans and their surroundings.

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