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Vehicle's Cabin Noise Reduction Techniques by Cost-Effective Embedded Processor

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Abstract: Noise cancellation is currently important in digital signal processing and cost-effective fidelity surrounding sound achievement. The current development of digital technologies helps in the implementation of digital signal processing on cost-effective processors. As transportation heavily depends on vehicles, noise generation within their cabins has become a predominant concern over different vehicles speeds. Earlier attempts for reducing cabin's noise involved analog electronics; however, the effectiveness of these approaches remains undocumented. In the recent times, digital signal processing has emerged as a preferred method for noise cancellation, yet an independent assessment of its efficiency is lacking.
This paper aims at implementing in-car noise cancellation via an embedded processor using two methods. The research emphasizes the effectiveness of digital noise cancellation in enhancing in-cabin environments by creating a quitter surround through acoustics techniques. In the first one, signals are generated inside a rectangular enclosure insulated from inside with a foam material. The signal is countered by an inverting noise signal of an equivalent amplitude and 180^{o} degrees out of a phase with no filtration. Typical obtained noise cancellation values are in the range of 7 to 11 dB, for all vehicle's speed.
The second approach involves a digital Finite and Infinite Impulse Response noise cancellation through Low-Pass filters (2nd, 5th, 10th orders), designed by MATLAB and implemented on the embedded processor. The 2nd order LP-FIR filter demonstrates superior outcomes, achieving reductions of approximately 19 dB, 15.3 dB, and 17.6 dB for the driver, passenger, and rear sides, respectively, for different vehicle's speeds. However, the 5th order BLP-IIR filter yields the highest noise reduction compared to the 2nd and 10th orders, as the average noise cancellation values are 11.6 dB, 10 dB, and 9.3 dB for the driver, passenger, and rear sides, respectively, at different speeds.

Keywords: *Analog Signal Filtration Techniques, Active Noise Cancellation, Digital Signal Filtration Techniques, Car Cabin's Noise*

1. Introduction

Despite the advancements of automobile manufacturing in safety, stability, cost, and driving comfort, noise reduction remains a big challenge facing car manufacturers. While driving, various noises are generated from different internal or external sources. Cabin noises may come from engine, exhaust, road-tire, carpet, wind, and body structure. These noise signals can cause driver's fatigue and loss of focus while driving. To ensure comfortable driving, internal noise should be cancelled or minimized [1].

The frequencies of these noise signals inside car can be classified into two types: broadband and narrowband. To attenuate and block broadband noise signals, a range of techniques are used, including absorber, mufflers, earplugs, ear-protectors, sound-absorbing materials, enclosures, and barriers, thus, this technique is referred to Passive Noise Cancellation (PNC) [2] [3]. PNC offers many benefits including simplicity without needing any active electronic system or power consumption [4]. However, the main drawbacks of this technique are its high cost, high weight, volume requirement, and less efficiency for narrowband frequencies. So, for attenuating narrowband frequencies, another technique is used which is called Active Noise Cancellation (ANC). Low frequencies (0 - 500 Hz) dominate these narrowband frequencies [5].

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ANC is based on the superposition principle and it employs an electro-acoustic system to cancel unwanted noise by introducing a noise-canceling signal possessing an equal amplitude and an opposite phase to the original noise signal. This counteracting signal aims to effectively cancel out the undesired noise [6] [7] as shown in Fig.1.

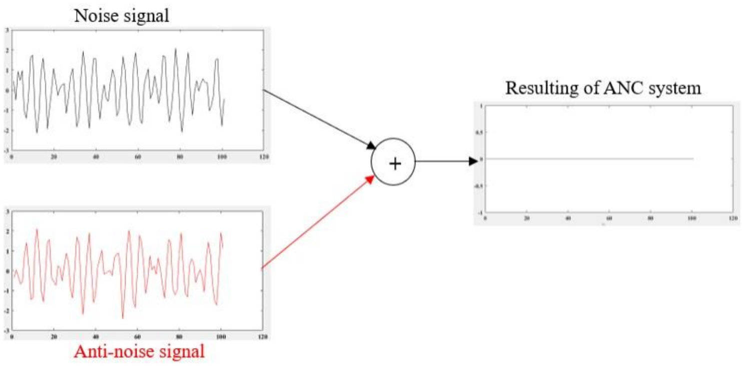


Fig 1: Active Noise Cancellation Principle

Over the past two decades, significant efforts have been made to address the issue of noise cancellation inside vehicles, stemming from various sources including engine noise, road-tire noise, and structure-borne noise, exhaust noise, etc. Numerous studies have explored the use of adaptive filter algorithms to tackle this challenge. However, a significant gap in most of the previous research lies in the fact that little attention has been given to the car cabin itself. Instead, the majority of studies have focused on canceling noise by controlling other vehicle components.

Technically, noise cancellation in vehicles is crucial for enhancing the overall comfort and driving experience. By canceling the unwanted noise, passengers can enjoy a quieter and more pleasant ride. Previous works have mainly concentrated on reducing noise from the engine, tires, and other parts of the vehicle, but they often overlook the interior cabin where passengers directly experience the noise. Considering cabin's noise control is essential to improve acoustic conditions and provide optimal environments for passengers, leading to increased customer satisfaction and driving comfort. Thus, further research should aim to develop innovative adaptive filtering approaches that directly target the cabin's noise cancellation, thus offering comprehensive solutions for noise reduction and improving the overall driving experience. The issue goes back to 1992 when Nissan car company claimed that it installed a noise suppression module inside their Nissan Bluebird model, but no independent data is available on how effective this module was.

Paul Sas and Wouter Dehandschutter [8] investigated multiple active control systems aimed at reducing road noise inside a mid-size station wagon when driving on other road surfaces. Adaptive feedforward control algorithms utilizing accelerometers and microphones were selected. Two control configurations were chosen. The first is a structural acoustic control which has inertial shakers on the suspension paths. The second is anti-noise system with loudspeakers inside the cabin. Laboratory and road tests were compared with the numerical simulations. Zibin Jia, et al [9] designed a modified simplified hybrid ANC (msHANC) and the overall noise reduction is 3.7 dBA.

Liping Zhu, et al [10] studied engine noise in a vehicle with and without a control system. A total of 52 microphones were employed to measure noise level inside car cabin. A 6.2 dB and 2.9 dBA noise reductions achieved inside the whole cabin through the control of the first four orders' engines. Also, Shi-Hwan Oh, et al, [11] introduced an innovative approach involving a leaky filtered-X LMS algorithms along with an IIR-based filter for a feedforward ANC system. The main aim was to minimize the booming noise generated by road conditions. The ANC system included four transducers of acceleration for detecting reference vibrations and two loudspeakers strategically positioned near the front seat headrests to effectively counter the noise. An in-depth analysis of the car's road-induced booming noise revealed a dominant frequency range, mainly concentrated around 250 Hz. In the test drive on rough asphalt and turtle-back road maintaining a consistent speed of 60 km/h, a reduction of 5-6 dBA in road booming noise was achieved. Particularly, this improvement could not be accomplished using the traditional multiple filtered-X LMS algorithm. Uwe Letens, et al, [12] focused on the problem of discomfort caused by road-induced low-frequency vibrations in estate cars. An experimental car was equipped with an ANC system, demonstrating the potential for reducing this noise and enhancing comfort. The research highlights that a minimal number of primary sensors can effectively attenuate cabin noise using a multiple-input feedforward control system. ANC system can reduce the noise signal inside the cabin by 6 to 8 dB, leading to improved subjective noise comfort in the estate car.

Thilagam and Karthigaikumar [13] emphasized many interior noise sources in a car such as engine and tire-road surface interaction and noises. They explored varied strategies, including passive and active control methods to mitigate these noise sources. To address this challenge, an ANC system was employed. This system utilized a modified Fx-LMS algorithm approach, incorporating a Digital Adaptive Filter known for its stability and rapid convergence in real-time environments. As a result, real-time noise within the car cabin exhibited reductions ranging from 3 to 13 dB, depending upon road surfaces and microphone placement.

Ji-guang Jiang and Yue Zeng [14] employed the FXLMS algorithm for mitigating low-frequency interior noise in vehicles. Through their developed hardware and control software, they effectively reduced noise near the driver's left ear, achieving reductions of 8.5 dB and 10.2 dB (linear scale) under steady driving conditions. The research confirms the effectiveness of the adaptive active noise control system in the reduction of the interior noise within vehicles, utilizing independent design and analysis.

This paper focuses on designing fixed digital filters and addressing the problems in designing ANC system for reducing noise signals inside the vehicle’s cabin. Fig.2 shows the designed ANC system. It included both PNC and ANC systems. For the evaluation of the effectiveness in noise decrease in the vehicle's cabin, the system was fitted inside a built-in rectangular enclosure. Within the PNC system, the noise-absorbing material chosen was Sound Insulation Foam Material (SIFM) with a thickness of 1.5 cm, emulating real-world car conditions.

The initial approach in designing an ANC system involves the direct inversion of the noise signal, while the second employs Low-Pass Finite Impulse Response (LP-FIR) and Butterworth Low-Pass-Infinite Impulse Response (BLP-IIR). Both methodologies make use of an Arduino embedded processor.Additionally, the assessment was conducted across varying vehicle’s speeds without loading the engine to ensure the attainment of optimal performance levels.

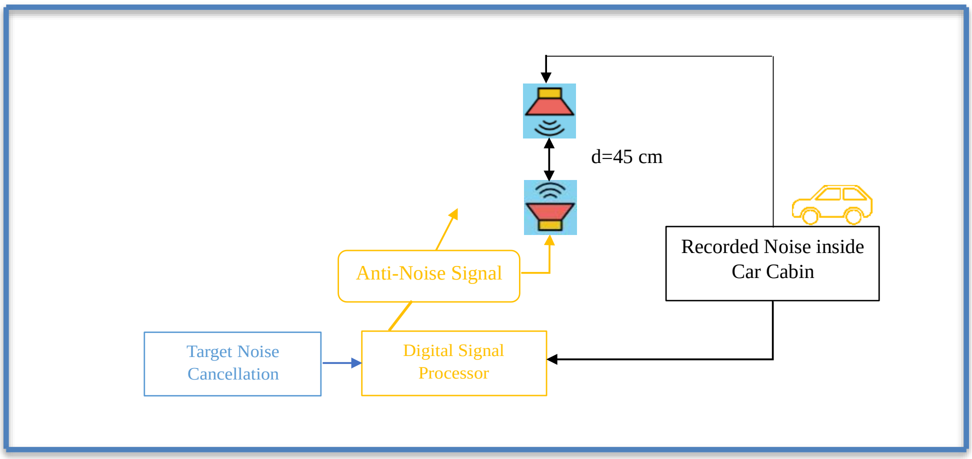


Fig 2: Active Noise Cancellation system inside rectangular enclosure

2. Methodology

Fig.3 shows the flowchart of the current research path. Toyota Yaris with 1.5-liter four-cylinder engine was used for the experiment setup and the overall procedure can be classified into four stages. In first stage, the noise signals are recorded inside the vehicle cabin under different conditions for different road profiles and velocities of the car. In the second stage, digital sound level meter is used for measuring sound pressure levels (SPLs) of the noise signals to make comparisons with SPL after noise cancellation or reduction. At the third stage, an ANC system was designed using Digital Filtration (DF) techniques, and the results obtained from each procedure are compared to select the best method. Finally, the system was installed inside the designed box and tested for various road profiles and vesicle's speeds.

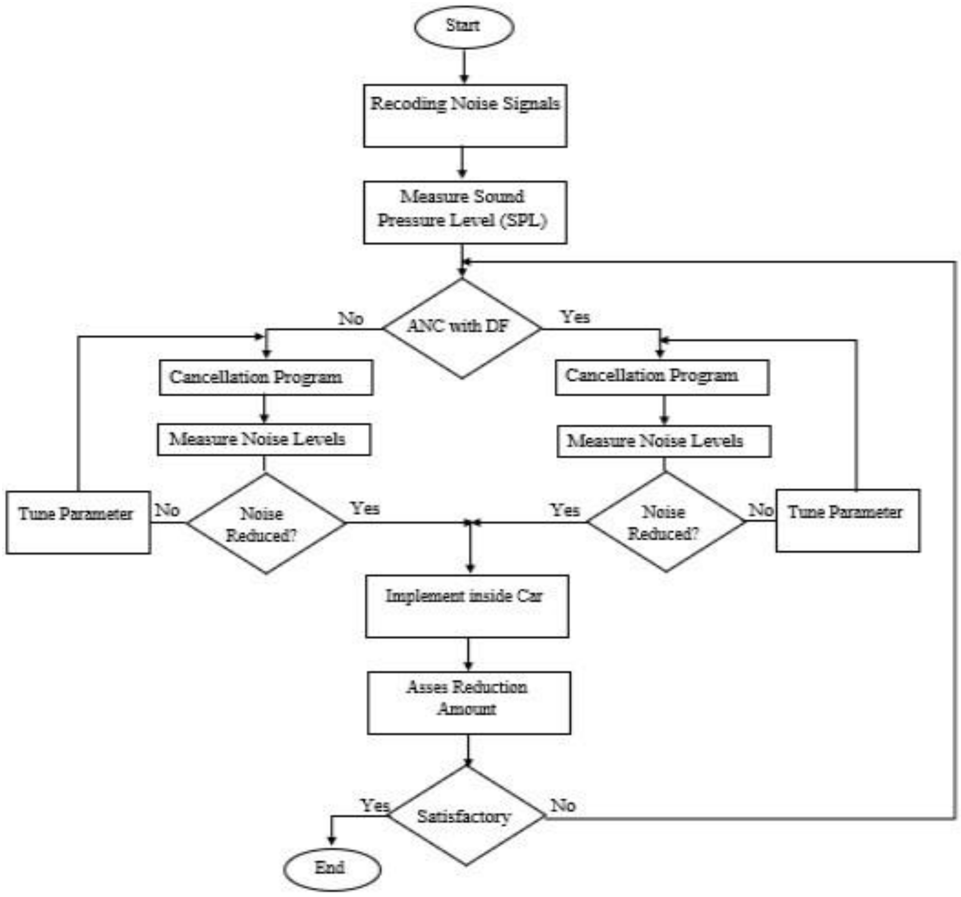


Fig 3: Processing steps flowchart

2.1. Digital Signal Processing

Digital Signal Processing (DSP) refers to the manipulation and analysis of digital signals using various mathematical algorithms and techniques. It involves processing signals that have been converted from analog to digital form, typically using analog-to-digital converters (ADCs). Once it is in the digital domain, the signals can be processed, analyzed, and transformed using various DSP algorithms. DSP offers several key benefits, including its ability to be programmed, providing a stable and tolerant output compared to analog circuits, and real time processing. Additionally, the digital signal processing techniques enable the realization of linear phase filters and steep-cut-off notch filters [15]. In general, DSP system can be classified into two techniques [16]:

1. Non-real-time: Signal processing includes modifying already-collected and digitized signals. The requirement for the outcome is independent of real-time [16].
2. Real-time: The design of DSP hardware and software must meet certain requirements in order for signal processing to execute predetermined tasks within a set amount of time [16].

The most significant part in digital signal processing are the sampling and filtration process. Both of them are discussed in the next sections.

2.1.1. Sampling Theorem

The analog signal $x(t)$ can be converted into the discrete-time signal $x[n]$ by using the sampling theorem, which states that Fs (sampling frequency) is [16]:

$$F_s = \frac{1}{T_s}$$

Ts is the sampling time, x(t) is Analog signal, f_s is Sampling rate or sampling frequency, and x(nT) is Discrete time signal, as shown in Fig.4.

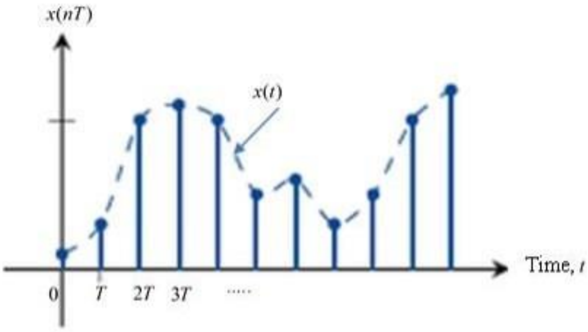


Fig 4: Analog signal and discrete-time signal

The analog signal x(t) needs to satisfy the following two requirements in order to be sampled to a discrete-time signal x(nT) [16]:

1) The analog signal x(t) needs to be bandlimited by the bandwidth of the signal f_m.
2) The sampling frequency f_s should at least be twice the maximum frequency component f_m in the analog signal:

$$f_s \geq 2f_m \; Shannon's \; sampling \; theorem$$

The Nyquist rate is achieved if the sampling frequency equals the highest frequency in the signal ($f_s = 2f_m$). The anti-aliasing filter is applied to the input signal to satisfy the sampling frequency that could be a low pass or band pass filter to prevent DC offset or other low-frequency noise [16]. Another important parameter in the sampling of the signal is the bit depth specifying the number of bits in each sample. The sound quality is in a direct link with the number of bits depth. The audio signals with bit depth of 16-bitsprovide a higher quality than the one with 8 bits, as shown in Fig.5 [17].

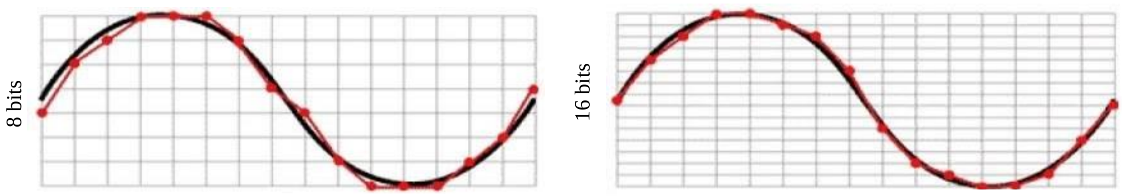


Fig 5: Effect of bit depth on signals [17]

2.1.2. Finite Impulse Response Filter (FIR Digital Filter)

A filter is a device for attenuating the undesired signal from a desired signal. The filter's primary roles are to enhance the quality of the signal and extract information from transmissions. Digital filter is classified into Finite Impulse Response (FIR) and Infinite Impulse Response (IIR) [16]. FIR systems are non-recursive and finite duration unit sample response. In other words, the value of h(n) is 0 for n<0 and 1 for n ≥ M. Therefore, the unit sample response exists for the duration 0 to M-1. Difference equation of the LSI system for FIR filters becomes [16]:

$$y(n) = \sum_{k=0}^{M} b_k \, x(n-k)$$

The structure of FIR filter is shown in Fig.6. FIR has many advantages including stability, a linear phase response, and reduced impact of quantization errors compared to IIR filters. They are characterized by an all-zero filter configuration. FIR filters are necessary in applications where maintaining a linear phase response is a critical requirement. For implementing FIR filter, it is essential to apply one of the appropriate methods such as Fourier series, Frequency sampling or Window method [16].

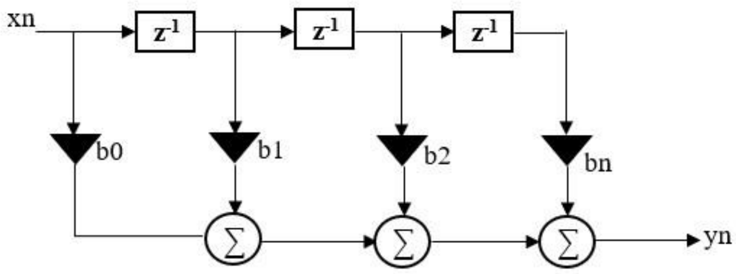


Fig 6: FIR filter structure

2.1.3. Infinite Impulse Response Filter (IIR Digital Filter)

Infinite Impulse Response systems are recursive. Thus, the output of IIR filter is dependent on the past and present inputs and the past outputs. The LSI system difference equation o for IIR filters is [16]:

$$y(n) = -\sum_{k=1}^{N} a_k y(-k) + \sum_{k=0}^{M} b_k x(n-k)$$

Fig.7 depicts the structure of IIR filter. The IIR filter's unit impulse response is infinite, or h(n) = 0 for n<0 and h(n)=1 for n<0. Stability and phase responses are two of IIR filter's main drawbacks. However, IIR filter is typically more effective in the computation time and memory requirements. IIR systems often require less storage and time for processing than other digital filters. Therefore, if a sharp cutoff and high throughput are required, IIR filters are typically used.

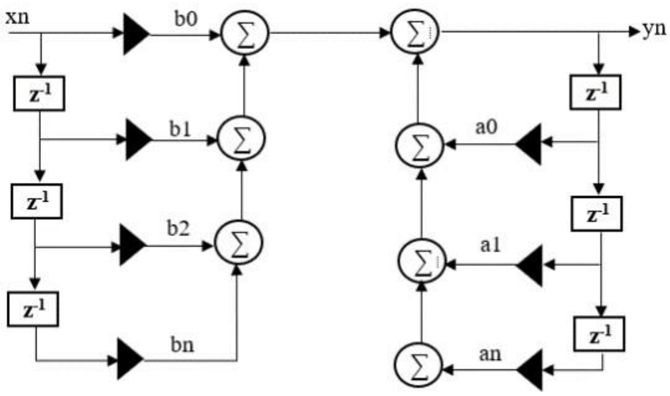


Fig 7: IIR filter structure

For designing the IIR filter, the following steps should be considered [16]:

1. Determining the analog filter transfer function: This is the starting point for designing the IIR filter. You can obtain the analog filter transfer function by using passive (Resistor, inductance, and capacitor) or active components (operational amplifier).
2. Then the analog transfer function is converted into the digital filter transfer by the use of one of the following techniques: bilinear transformation or impulse invariance.
3. Choosing the filter order: The filter order is the number of poles and zeros in the filter transfer functions. A higher order filter has a sharper cutoff but requires more computational resources. The filter order is usually determined by the filter specifications.
4. Determining the cutoff frequency: The cutoff frequency is the frequency at which the filter response starts to roll off.
5. Designing the filter coefficients: After obtaining the filter transfer function, filter order, and cutoff

frequency, you can design the filter coefficients and select IIR filter types (Butterworth, Chebyshev, Elliptic, Bessel, High pass, Band Pass, Band Stop) according to the requirements.

6. Implementing the filter: The final step is to implement the filter using a digital signal processing algorithm or hardware.

In this paper a LP-FIR and BLP-IIR filters were designed. Thus, it is necessary to identify some parameters related to the LPF filters and their types as shown in Fig.8.

1. Cut-off frequency (f_c) separates pass band and stop band [18].
2. Pass band frequency (f_p): This frequency passes certain frequency range. In the pass band, attenuation is 0 [18].
3. Stop band frequency (f_s) suppresses certain ranges of frequencies and the stop band has an infinity attenuation [18].

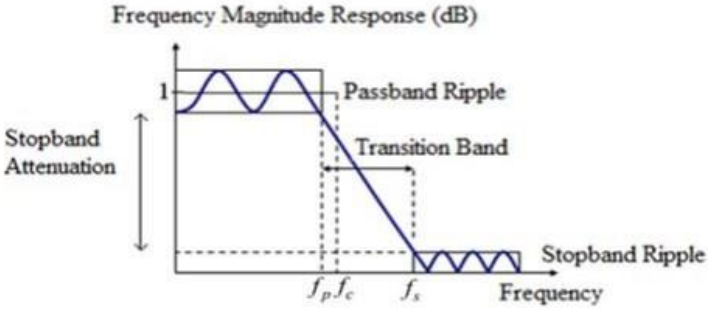


Fig 8: Magnitude response of the LPF

2.2. Characteristics of Road Profile

For many decades, researchers and acoustic engineers have worked in the vehicle and tire industries to cancel or minimize noise signals. Quietness is the customer's requirement parameter of concern in designing and advertisement of new vehicle. A quieter car provides more comfort and gives the driver a sense of driving a luxuries car. Generally, the noise signal in the vehicle can be a tire road and power unit noise [1]. Tire road noise is generated because the tire interacts with the road surface and pavements [19] [20]. The power unit noise consists of the engine noise, exhaust system and transmission noise. Tire, road and power unit noise(s) are closely related to the velocity of the vehicle and they increase logarithmically with its velocity [21].

Noises produced by tires are usually of broadband nature, so the analysis of the noise signal and frequency spectrum is required for real time implementation. MATLAB and Visual analyser software (https://visual-analyser. software.informer. accessed and downloaded on January of 2023) are used to obtain frequency analysis of the noise signals. A study [22] considered different road profiles such as low roughness (Dukan road), medium roughness (Qaradagh road), high roughness (Mergapan road). Based on the obtained results, there are small differences between them, hence in this paper only medium roughness road is considered. Fig. 9 shows the frequency analysis for the driver side of the tested car with various vehicle's speeds of 50 Km/h, 70 Km/h, and 90Km/h. This analysis shows that the noise signal has two peak values in the range 40 to 60 Hz and 80 to 100 Hz.

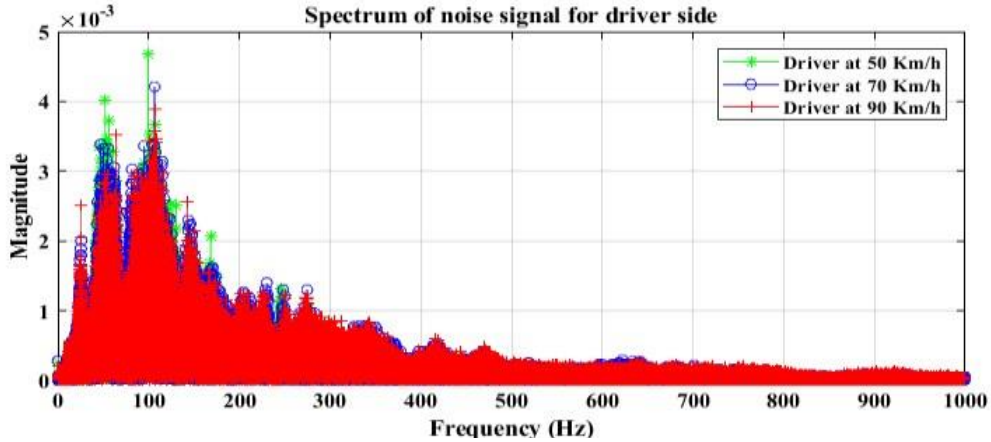


Fig 9: Spectrum of noise signal for driver side at various vesicle's speeds

Fig.10 shows the frequency spectrum for passenger side of the tested car with three vehicle's speeds of 50 Km/h, 70 Km/h, and 90Km/h. It's observed that most noise signal components are below 200 Hz. The major frequencies components of the noise signal is 20 Hz, 40Hz and 60 Hz.

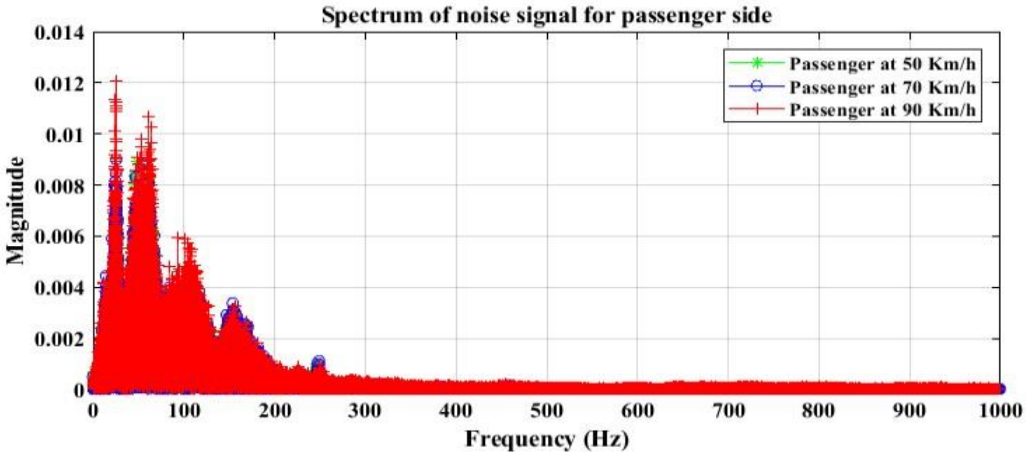


Fig 10: Spectrum of noise signal for passenger side at various vesicle's speeds

Fig.11 shows the frequency spectrum of car's rear side (for the tested car) with the same three vehicle's speeds of 50 Km/h, 70 Km/h, and 90Km/h. The main peak value of the noise signal is between 40 to 60 Hz.

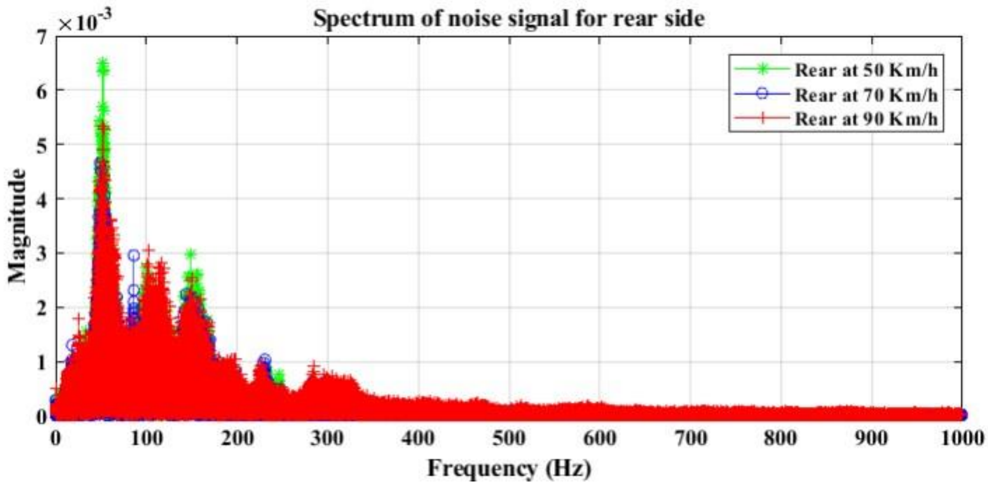


Fig 11: Spectrum of noise signal for rear side at various vesicle's speeds

The spectrum of the noise signals is also analyzed by using Visual analyzer software. It has been noticed that the main noise signals components are at 40 to 100 Hz for the driver side, and 40 to 60 Hz for the passenger and the rear sides of the vehicle [23]. The frequencies of 40 – 60 Hz are most common in all parts of the vehicle, as shown in Table 1. Thus, frequency components inside the car's cabin are narrowband and are below 200 Hz.

Table 1: Summarization of frequency analysis for Qaradagh road

Frequency (Hz)	**Driver side**			**Passenger side**			**Rear side**		
	50Km/h	70Km/h	90Km/h	50Km/h	70Km/h	90Km/h	50Km/h	70Km/h	90Km/h
20					√	√			
40	√	√	√	√	√	√	√	√	√
60	√	√	√	√	√	√	√	√	√
80		√	√						
100	√	√	√						√
120									
140							√	√	

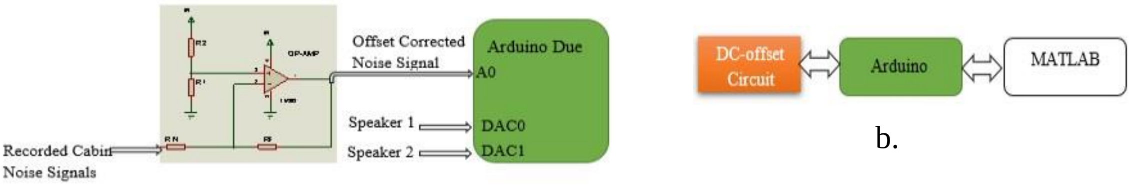
3. Challenges to ANC

Researchers and designers investigated and developed ANC systems; however, the utilization of an effective ANC system is frequently restricted to narrow regions. The following are some problems related to the ANC systems:

1. The environmental noise issues are random, transient, unstable, and mobile. They are usually spread in a large unbounded area [24].
2. The match between primary and secondary sources is considered in a specific target area in a local control way. The local control method's efficiency relies on the distance of the primary source from the secondary source with an error sensor. The minimum space between each secondary source and error sensor would be 0.1m [24].
3. Another problem with this technology is the high cost of the system. The practical application of the ANC is realized by minimizing the cost or by the huge improvement of performance. The ANC system can cancel the noise signal frequency below 500Hz, but it may be very problematic to use an ANC to obtain noiseless exposure to higher frequency ranges. Even if it is achieved, the cost would be unrealistic [25].
4. When the secondary source generates an anti-noise signal, it propagates the upstream to the reference input, which is an unwanted acoustic feedback signal that corrupts the primary signal x(n) [26].
5. In several practical applications, the reference frequency x(n) is different from the primary noise d(n) in the error sensor position; this damages the performance of the system [26].
6. Another problem is the ANC system's scope as different types of noise may require different manipulations and processing [26].

4. Hardware System

In this paper, cabin noise signals are cancelled by using two different approaches. In the first method, the noise is cancelled by generating a counter wave of the unwanted signal inside a designed rectangular enclosure as shown in Fig.12a. Since Arduino's can only can read positive voltages in the range of 0V to 3.3 V, an offset circuit is used to bias the signal and read negative voltages parts before getting processed by the processor. The digital Low-Pass filters are used in the second technique to remove the cabin noise. The parameters of the filter a_n and b_n are calculated by the MATLAB program and then transferred to the Arduino IDE software as shown in Fig.12b.



a. b.

Fig 12: Embedded processor-based implementation

5. Results and Discussion

Noise signal and counter noise signal are shown in Fig.13, in which the blue color represents the noise signals and the yellow color is the anti-noise signal, inverted by 180o with the same amplitude.

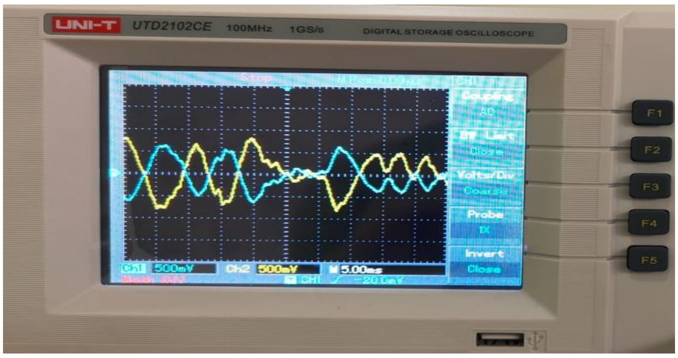


Fig 13: Noise signal and anti-noise signal inside vehicle's cabin

For all the figures, the noise signal inside the cabin is depicted by the black line. The red line shows the Mean value (average) of the noise when the designed box is covered by SIFM, and the gray line is the Mean noise value with a 2nd order digital Low-pass filter. The blue line shows the average noise cancellation due to 5th order digital Low-Pass Filter and finally, the green line refers to noise cancellation due to the 10th order digital Low-pass filter. The y-axis shows the SPL noise reduction in dB while the x-axis is the different vehicle sides (driver, passenger, and rear sides).

For the driver, passenger, and rear sides of the vehicle, a 7 dB reduction was obtained in the rectangular box without using SIFM and speaker distance of 45 cm in-between at various speeds [22].

Fig.14 illustrates the application of varied approaches to noise cancellation. At speeds of 50 Km/h, 70 Km/h, and 90 Km/h, the average noise level within the cabin's driver side measured was 77.33 dB. Correspondingly, the average noise levels for the passenger and rear sides across all speeds registered are 71.33 dB and 76 dB, respectively. The utilization of SIFM resulted in a noise reduction is in the range of 7 to11 dB for all vehicle's speed.

Through the utilization of the digital LP-FIR filter with various orders and a 200 Hz cut-off frequency (selecting the cut-off frequency relied on the spectrum analysis of the noise signal at driver, passenger, and rear sides as discussed in section 2.2), a better noise reduction was achieved. The 2nd order LP-FIR filter demonstrates superior outcomes, achieving reductions of approximately 19 dB, 15.3 dB, and 17.6 dB for the driver, passenger, and rear sides, respectively, for different vehicle's speeds. As, the filter order increases, the phase shift also increases, potentially affecting the system performance. The ANC system has the ability to eliminate noise that is highly correlated with the reference input. However, when there are uncorrelated noises in both the primary and reference inputs, the performance of the ANC system is compromised and degraded [9], [27].

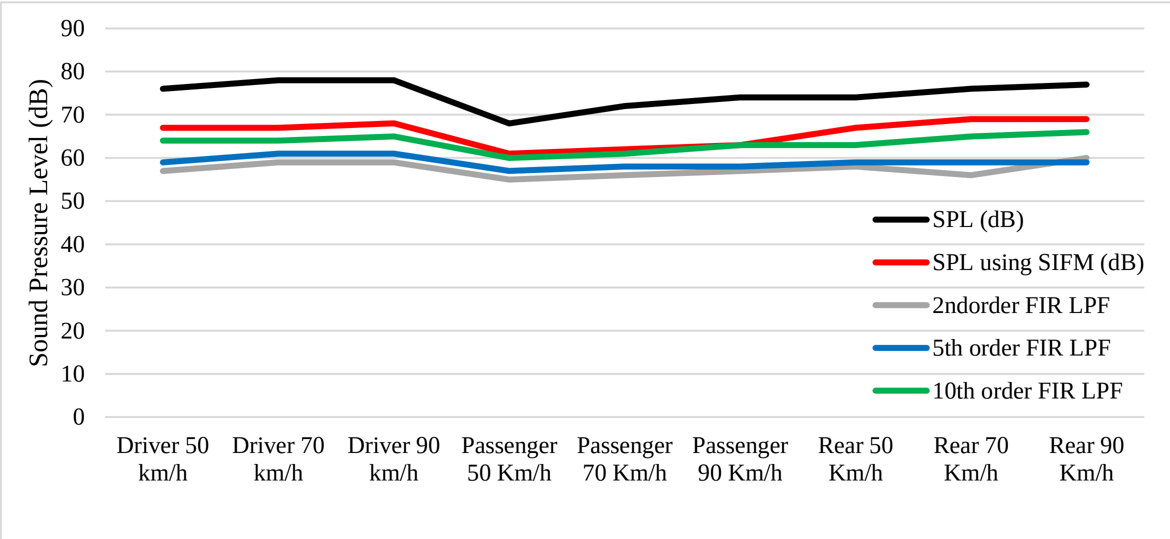


Fig 14: Noise cancellation by using SIFM and various digital LP-FIR filter inside vehicle's cabin

Fig.15 shows the noise cancellation results achieved through SIFM and digital BLP-IIR filter with 2nd ,5th, and 10th, filter order and cut-off frequency of 200 Hz. It is important to note that the noise signal includes diverse frequency components, and due to the non-constant phase response of the IIR filter, each frequency undergoes a distinct phase shift. As a consequence, the signal becomes distorted influencing the overall system performance.

Notably, the 5th order BLP-IIR filter yields the greatest noise reduction. This can be attributed to its nearly linear phase response, resulting in an average noise cancellation of 11.6 dB, 10 dB, and 9.3 dB for the driver, passenger, and rear sides, respectively, at different vehicle's speeds. This observation emphasizes the involved relationship between filter order, phase response, and the effectiveness of noise reduction.

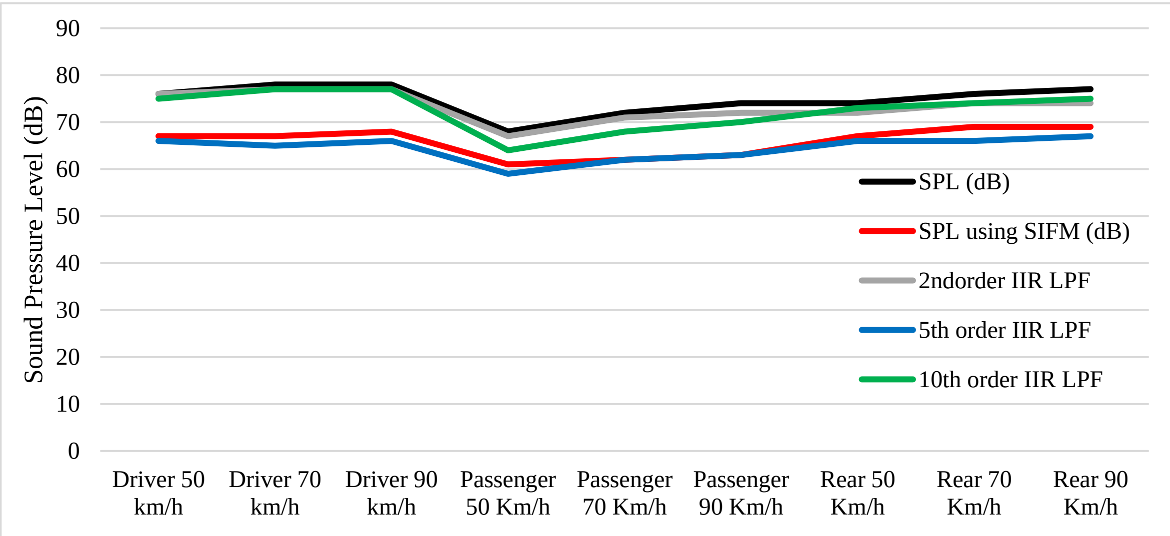


Fig 15: Noise cancellation by using SIFM and various digital BLP-IIR filter inside vehicle's cabin

Fig.16 presents a comprehensive comparison between the 2nd order LP-FIR filter and the 5th order BLP-IIR filter. The distinction between these filters is notable in terms of noise reduction effectiveness. The 2nd order LP-FIR filter exhibits superior noise reduction capabilities, primarily attributed to its linear phase response. This characteristic produces a higher degree of stability in the filter's performance. The linear phase response ensures that different frequency components experience consistent phase shifts, minimizing signal distortion. Thus, the FIR filter offers more noise cancellation, contributing to a more refined and accurate noise reduction outcomes.

In contrast, the 5th order BLP-IIR filter introduces varying phase shifts due to its non-constant phase response. This variability across frequencies can lead to signal distortion and potential compromise in noise reduction performance. While the BLP-IIR filter may still contribute to noise reduction, the linear phase response and stability of the 2nd order LP-FIR filter nominate it as a reliable choice for achieving a significant noise reduction.

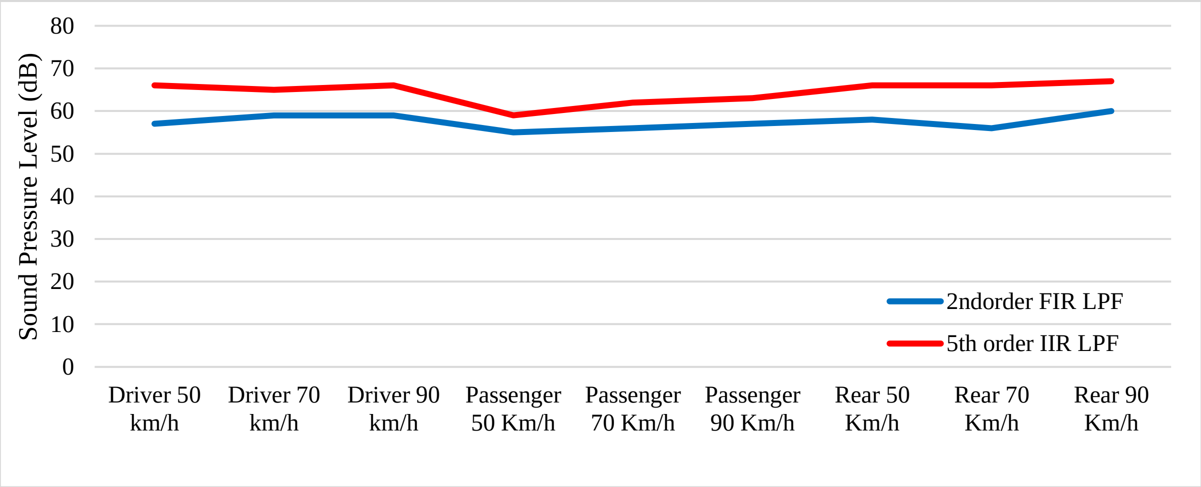


Fig 16: Comparing between 2nd order LP-FIR filter and 5th order BLP-IIR filter

The ANC system holds the capability to cancel out noise of identical amplitudes. However, any dissimilarity in amplitudes between the noise signal and the anti-noise signal can impact the performance of the ANC system. Fig.17 provides a visual difference between the amplitude of the noise signal and the corresponding anti-noise signal. To facilitate this comparison, the oscilloscope's inverted function was intentionally set to open, serving the specific purpose of explaining amplitude variations

Fig 17: Comparison between noise signal and anti-noise in term of amplitude

Table 2 demonstrates how the amplitude of the anti-noise signal impacts the performance of the ANC system. The assessment focuses on the system performance utilizing the 2nd order BLP-IIR filter. The anti-noise signal amplitude is controlled by a scaling factor. When the scaling factor is set to 0.28, the noise reduction levels at speeds of 50 Km/h, 70 Km/h, and 90 Km/h reaches 4 dB, 1 dB, and 3 dB, respectively. However, when the amplitude of the anti-noise signal increased to 0.4, a clear improvement in noise cancellation effectiveness is achieved. This enhancement results in a significant noise reduction value of 10 dB, 7 dB, and 9 dB for speeds of 50, 70, and 90 (Km/h), respectively. This observation highlights the crucialness of the anti-noise signal amplitude to the ANC system noise cancellation process performance.

Table 2: SPL Comparison between amplitude of noise signal and anti-noise signal for driver side

Side/speeds	Average noise signal (dB)	Scaling Factor= 0.28	Scaling Factor= 0.4
		Average noise reduction using 2nd BLP-IIR (dB)	Average noise reduction using 2nd BLP-IIR (dB)
Driver 50 Km/h	67	63	57
Driver 70 Km/h	67	66	60
Driver 90 Km/h	68	65	59

6. Conclusion

The work concludes a dual noise cancellation system comprising both PNC and ANC that were implemented through two approaches. The first is with utilizing SIFM (with an inverted noise signal) and the second is through applying digital LP-FIR and BLP-IIR filters (with different orders).

Filters were designed in MATLAB and executed on an embedded processor. The LP-FIR technique exhibited a superior noise decrease than other methods, attributed to the advantages of linear phase, minimal group delay, and stability. While an IIR filter exhibits a non-linear phase response characteristic, as certain frequencies align in phase with the input signal's amplitude after cancellation, this results in increased signal values for those frequencies, ultimately causing a decline in performance that cannot be avoided. This research underlines the potential of digital noise cancellation techniques and their practical application in enhancing in-cabin acoustics environment and the driver's experiences during different driving conditions. It emphasizes the role of hybrid approaches in creating a quieter environment and highlights the phase response and an amplitude synchronization importance in optimizing noise cancellation.

References

[1] P. N. Samarasinghe, W. Zhang and T. D. Abhayapala, "Recent advances in active noise control inside automobile cabins: Toward quieter cars," IEEE Signal Processing Magazine, vol. 33, no. 6, pp. 61-73, 2016.

[2] M. A. Sahib and S. Streif, "Design of an Active Noise Controller for Reduction of Tire/Road Interaction Noise in Environmentally Friendly Vehicles," Signal Processing: Algorithms, Architectures, Arrangements, and Applications (SPA). IEEE, pp. 59-62, September 2017.

[3] J. Dungel, P. Zvolenský, J. Grenˇcík and J. Krivda, "Investigation of Noise Generated by Railway Freight Wagon Bogie Type Y25Ls (s) eK and Proposals of Noise Reduction," Vehicles, vol. 4, no. 1, pp. 124-136, 2022.

[4] B. Lam, W.-S. Gan, D. Y. Shi, M. Nishimura and S. Elliott, "Ten questions Concerning Active Noise Control in the Built Environment," Building and Environment,200, p. 107928, 2021.

[5] P. Nelson and S. Elliott, Active Control of Sound, Academic Press, 1991.

[6] Y. Song, "Active Noise Cancellation and Its Applications," In Journal of Physics: Conference Series. IOP Publishing, vol. 2386, no. 1, p. 012042, 2022.

[7] S. M. Kuo, "Adaptive Active Noise Control Systems: Algorithms and Digital Signal Processing (DSP) Implementations," In Digital Signal Processing Technology: A Critical Review. SPIE, vol. 10279, pp. 26-52, 1995.

[8] P. Sas and W. Dehandschutter, "Active Structural and Acoustic Control of Structure-Borne Road Noise in a Passenger Car," Noise and Vibration Worldwide, vol. 30, no. 5, pp. 17-27, 1999.

[9] Z. Jia, X. Zheng, Q. Zhou, Z. Hao and Y. Qiu, "A Hybrid Active Noise Control System for the Attenuation of Road Noise inside a Vehicle Cabin," Sensors, vol. 20, no. 24, p. 7190, 2020.

[10] L. Zhu, X. Zhong, H. Wang, X. Qiu, S. Wu and D. Mao, "An Objective and Subjective Study on Global Active Control of Engine Noise in a Car," Journal of Vibration and Control, p. 10775463231174730, 2023.

[11] S.-H. Oh, H.-s. Kim and Y. Park, "Active Control of Road Booming Noise in Automotive Interiors," The Journal of the Acoustical Society of America, vol. 111, no. 1, pp. 180-188, 2002.

[12] . Letens, G. Koners and T. J. Saunders, "Adaptive Road Noise Cancellation for a Midclass Estate Car," The Journal of the Acoustical Society of America, 105(2_Supplement), pp. 1243-1243, 1999.

[13] S. Thilagam and P. Karthigaikumar, "Implementation of Interior Noise Control System using Digital Adaptive Filter for on-Road Car Applications," Wireless Personal Communications, vol. 104, pp. 339-356, 2019.

[14] J.-g. Jiang and Y. Zeng, "Adaptive Active Control System of Vehicle Noise Design and Test," Advanced Materials Research, vol. 1028, pp. 251-256, 2014.

[15] N. Kehtarnavaz, Real-Time Digital Signal Processing: based on the TMS320C6000, Newnes, 2004.

[16] S. M. Kuo and B. H. Lee, Real-Time Digital Signal Processing: Implementations, Applications and Experiments with the TMS320C55X, Hoboken, NJ, USA: Wiley, 2001.

[17] A. N. Naeem and S. Ramadass, "A Review on Audio Sampling Rates Mismatch and Its Effect on the Acoustic Echo Cancellation of Personal Computers.," Australian Journal of Basic and Applied Sciences, vol. 5, no. 9, pp. 1599-1605, 2011.

[18] S. Dogra and N. Sharma, "Comparison of different Techniques to Design of Filter," International Journal of Computer Applications, vol. 97, no. 1, 2014.

[19] Z. Shi, B. Liu, H. Yue, X. Wu and S. Wang, "Noise Reduction of Two-Speed Automatic Transmission for Pure Electric Vehicles," Vehicles, vol. 5, no. 1, pp. 248-265, 2023.

[20] S. Adachi and H. Sano, "Application of Two-Degree-of-Freedom Type Active Noise Control using IMC to Road Noise inside Automobiles," In Proceedings of 35th IEEE Conference on Decision and Control, vol. 3, pp. 2794-2795, 1996.

[21] U. Sandberg, Tyre/Road Noise Myths and Realities, Statens väg-och transportforskningsinstitut, 2001.

[22] A. R. Hamza and M. A. Hussein Shiekh, "Design and Implementation of Active Noise Cancellation for Car Cabin on Sulaimania Roads Using Arduino Embedded System," Journal of Engineering, vol. 28, no. 9, pp. 45-69, 2022.

[23] M. Herrmann, J. Kralicek, W. Stein and F. Gauterin, "Describing Road Booming Noise with a Hybrid Simulation Model Using a Time Segmentation of the Excitation Load Approach," Vehicles, vol. 3, no. 3, pp. 469-479, 2021.

[24] H. W. Z. L. K. a. L. H. Lee, " A review of active noise control applications on noise barrier in three-dimensional/open space: Myths and challenges," Fluctuation and Noise Letters, vol. 18, no. 4, pp. 1930002-1 -1930002-21, 2019.

[25] H. I. T. T. A. T. K. a. N. Y. Sano, " Active control system for low-frequency road noise combined with an audio system," IEEE Transactions on speech and audio processing, vol. 9, no. 7, pp. 755-763, 2001.

[26] S. K. K. a. G. W. Kuo, "Active Noise Control: Open Problems and Challenges," In The 2010 International Conference on Green Circuits and Systems. IEEE, pp. 164-169, June 2010.

[27] T. Lampl, "Implementation of Adaptive Filtering Algorithms for Noise Cancellation," 2020.