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Design of Low-Cost Active Noise Cancellation System for Automobile

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Abstract*:* The noise in the automobile affects the driving experience. The noise in the car is dominated by low-frequency noise which can be effectively reduced by active noise cancellation (ANC). The commercial ANC system employed in the car is often adopting digital signal processing (DSP) to achieve noise cancellation, in which the cost is relatively high, and it is pre-built in the automobile itself. In this work, a low-cost portable analog ANC system is designed to cancel the noise in the automobile. Extensive experimental tests are carried out to suppress the single-tone noise in the automobile, ranging from 100Hz to 500Hz in a frequency step of 100Hz. The proposed ANC system managed to reduce a maximum of 16.7dB of noise at 200Hz and a minimum of 1.7dB of noise at 400Hz. The results show that the analog ANC system designed can significantly reduce the low-frequency noise in the automobile.

Keywords: *Active Noise Cancellation, automobile, low-frequency noise*

1. Introduction

Automobiles have become a part of human daily life as the car becomes the main transport for travelling from one place to a different place in the last two decades. People these days pay plenty of time in the car every day. Many sorts of sounds or noises can be heard by the passengers and driver in the car. The noise sources mainly come from the engine, tire, exhaust, traffic, and wind. These noises are typically dominated by low-frequency sound which is in the acoustic range between 0-500Hz [1]. These kinds of noise degrade the comfort of both the passenger and driver travelling a long journey. Noise can cause a road accident to have happened as the noise causes driver fatigue. Hence, providing a quiet and comfy driving environment can contribute to road safety [2]. Moreover, the noise in the car additionally brings disturbance and disruption which eventually causes health and psychological impacts on the driver and passengers [3]. In line with the study on the impact of noise on health, “Disease Burden Caused by Noise Pollution” carried out by the World Health Organization and the European Union cooperative research center, prolonged noise exposure might cause serious effect on sleep and psychological health. It should additionally cause learning disabilities and diseases like tinnitus, and it might raise the danger of cardiovascular diseases [4].

Therefore, the comfortableness of a car becomes a crucial concern to purchase a car. The automobile industry today emphasises the reduction of interior cabin noise and endeavours for more economical and lightweight designs. As a result, the car interiors became noisier as the structural vibrations augmented. In general, acoustic noise is minimized through two methods, Passive noise Cancellation (PNC) and Active Noise Cancellation (ANC). Traditionally, the noise problem was mitigated through the PNC by installing structural damping and acoustic absorption [1]. Nevertheless, the PNC is outperforming in suppressing high-frequency noise, but it is less effective in low-frequency noise [1-3]. Meanwhile, the equipment for passive noise cancellation is expensive. Given the problem stated, ANC has been devised. The ANC was first proposed in the early 20th century. It is an effective noise minimization method that has the capability of suppressing undesired low-frequency noise (usually below 500Hz) electronically [5]. The fundamental concept of ANC in reducing unwanted noise is based on destructive interference. This can be achieved by generating an anti-noise signal which is equal in magnitude but opposite in phase. Ideally, when the noise signal and anti-noise signal come together, they will cancel out each other.

The anti-noise signal in fact can be generated through two methods, which are using the analog method and digital method. The analog method is implemented using discrete components such as an operating amplifier, resistor, and capacitor. This method has the advantage in cost and power as the discrete components are cheap and dissipate low power. The digital method is achieved by implementing the Digital Signal Processing (DSP) algorithm. The common algorithms are Least Mean Square (LMS) and Filtered-X Least Mean Square (FxLMS). These algorithms can be implemented using the microcontroller development board, DSP development board, and Field Programmable Gate

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Array (FPGA) development board. These development boards are usually high-cost. An external analog to digital converter (ADC) and an external digital to analog converter (DAC) is often needed in this method. The low cost analog feedback active noise cancellation system is proposed to cancel the indoor noise [10]. Return to the main topic, the ANC system is capable to create a quiet and comfortable zone that allows the drivers and passengers to enjoy the drive more and can have a piece of clearer music or conversation. Luxury cars have built-in ANC systems. The disadvantage of the built-in ANC system is that it cannot be brought from one car to another car. To own an ANC system, one must buy a luxury car with a pre-install ANC. Therefore, it is essential to have a low-cost ANC system for the automobile so that everyone can possess a comfortable environment when travelling to their destination.

2. Active Noise Cancellation System

The proposed ANC system was designed using analog circuitry to reduce the noise of 100Hz-500Hz in the car. The main function of the circuitry is to generate an anti-noise signal. The main component blocks and circuit schematics of the ANC system are depicted in Figure 1 and Figure 2 respectively. The first op-amp is a microphone amplifier follows by an inverting amplifier. The third and fourth op-amps are the 3rd order low-pass filter. The last op-amp is the all-pass filter. The overall circuit achieved a gain of 31dB with a 3kHz cut-off frequency. The essential modules of the ANC system are described as follows.

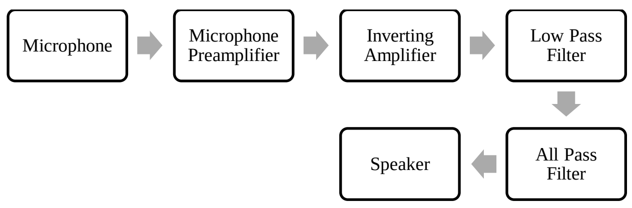

Fig. 1. The block Diagram of the ANC System

2.1. Microphone

The function of the microphone is to capture or detect the noise signal in the car. The signal is then transmitted to the microphone preamplifier.

2.2. Software

Since the signal from the microphone is too weak, the microphone preamplifier plays the role to amplify or strengthen the signal before passing to the next stage. To have a good ground reference for the amplifying stage, the value of the R3 (from Figure 2) is chosen to be 1MΩ. C2 (from Figure 2) together with R3 form a high pass filter to block the DC before the signal is amplified. The gain of the amplifier is calculated as follows:

$$A_v = 1 + \frac{R_4}{R_5} = 34 \tag{1}$$

Therefore, the gain of the amplifier is 34 or approximately 31dB. This means that the output voltage of the amplifier is 34 times greater than its input.

2.3. Inverting amplifier

The inverting amplifier is used to invert the noise signal from the previous stage to be the anti-noise signal which is 180° out of phase with the noise signal. The gain of the inverting amplifier is calculated as follows.

$$A_v = -\frac{R_7}{R_6} = -1 \tag{2}$$

This inverting amplifier has a unity gain. The negative indicates that the signal is inverted or has a phase shift of 180°. The gain keeps it as a unity by choosing R6 and R7 equal to 10kΩ (from Figure 2).

2.4. Low-Pass Filter

The low-pass filter filtering out or blocking the high-frequency signal to go to the next stage. It also has the function of reducing the high-frequency noise in the circuit. The cut-off frequency is chosen to be 3kHz is because the

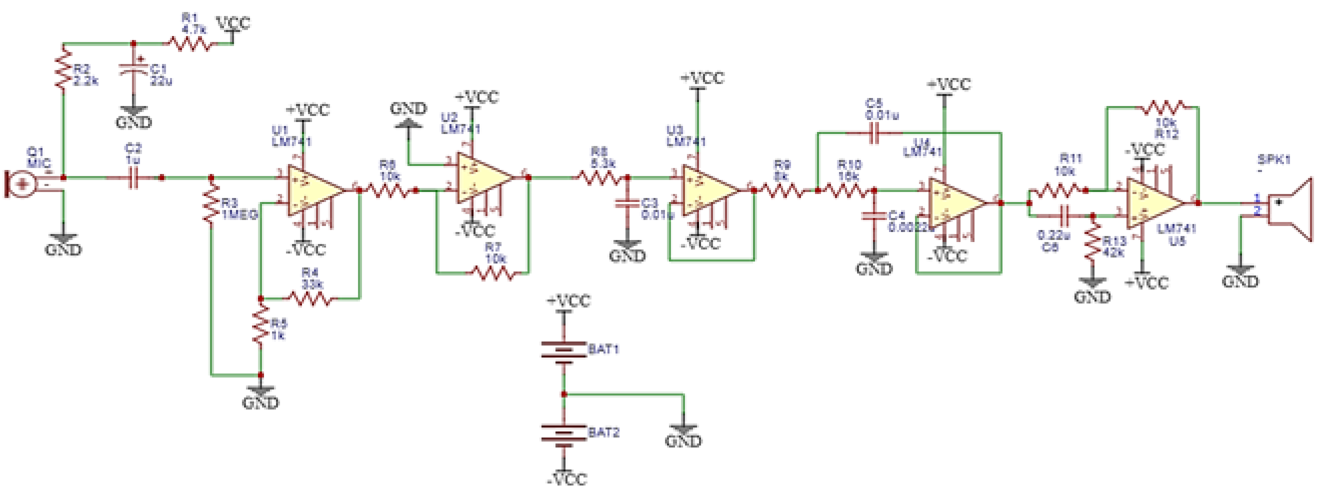

Fig. 2. The schematic diagram of ANC system

target frequency is 100Hz-500Hz and this range of frequency should be in the flat zone in the frequency response so that it would not have signal attenuation. Besides, the cut-off frequency was chosen to be 3kHz to minimize the phase shift caused by the low-pass filter, so that the noise cancellation can be achieved.

2.5. All Pass Filter

The all-pass filter is acted as the phase shift compensator. The gain of this filter is 1 because of $R_{11} = R_{12}$ (from Figure 2). The cut-off frequency is computed as follows.

$$f_c = \frac{1}{2\pi RC} = \frac{1}{2\pi(54k)(0.22\mu)} = 13.4Hz \qquad (3)$$

This means that the phase lead at 13.4Hz is 90° and it is decreasing to 0° as the frequency increases.

2.6. Speaker

The anti-noise signal is emitted or played through the speaker.

Table 1. The phase shift of the Low-Pass filter

Frequency (Hz)	Phase Shift (°)
100	-3.8170
200	-7.6255
300	-11.4171
400	-15.184
500	-18.9181

3. Simulation and Experimental Results

Extensive simulations were carried out to evaluate the performance of the ANC system. Figure 3 to Figure 7 show the simulation result of the sum of the input signal and the output signal from 100Hz to 500Hz. The green signal is the input signal, the red signal is the output signal, and the blue signal is the sum of the input and output signals. The blue signal indicates how much noise can be reduced by the ANC system proposed. From the simulation results, maximum noise reduction is achieved at 200Hz, then follow by 300Hz, 400Hz, 500Hz, and 100Hz.

Extensive experimental works were carried out to evaluate the ANC system on the single-tone noise reduction and noise cancellation in the car.

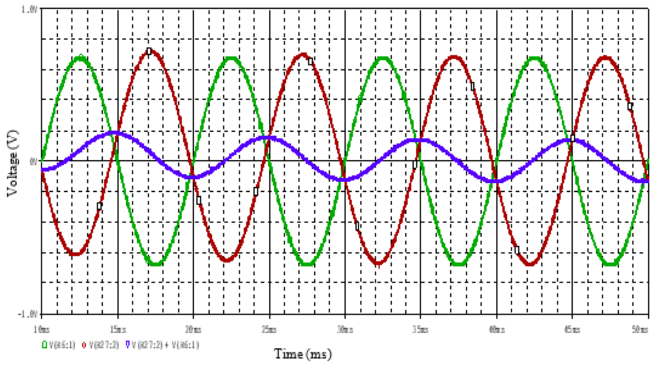

Fig. 3. Sum of Input Signal and Output Signal (100Hz)

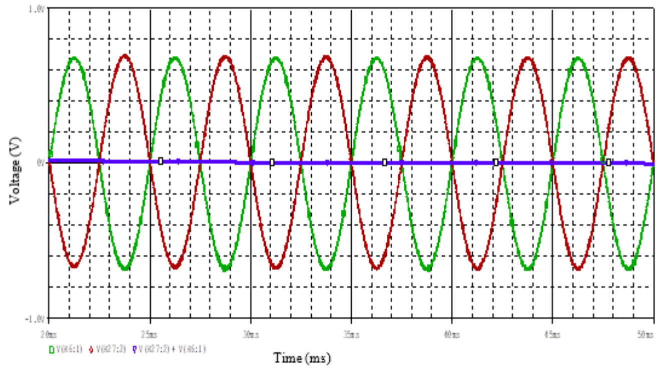

Fig. 4. Sum of Input Signal and Output Signal (200Hz)

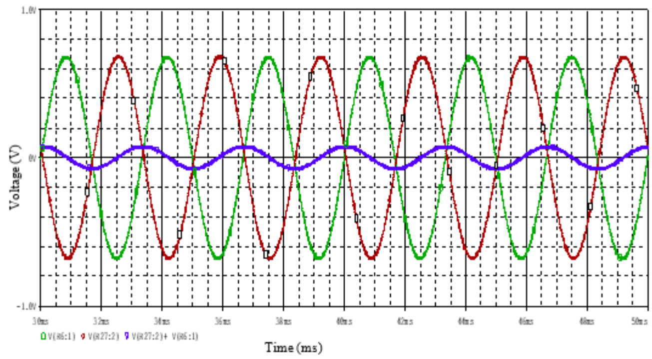

Fig. 5. Sum of Input Signal and Output Signal (300Hz)

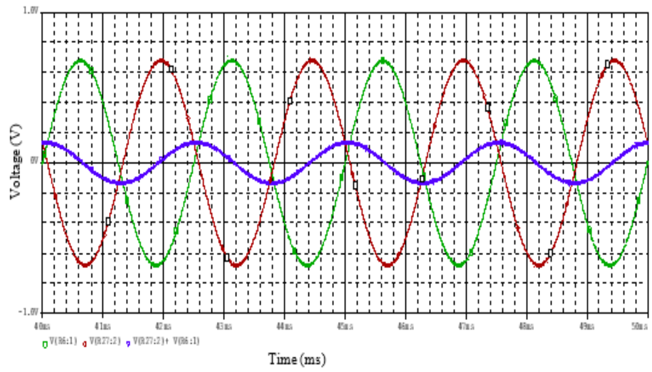

Fig. 6. Sum of Input Signal and Output Signal (400Hz)

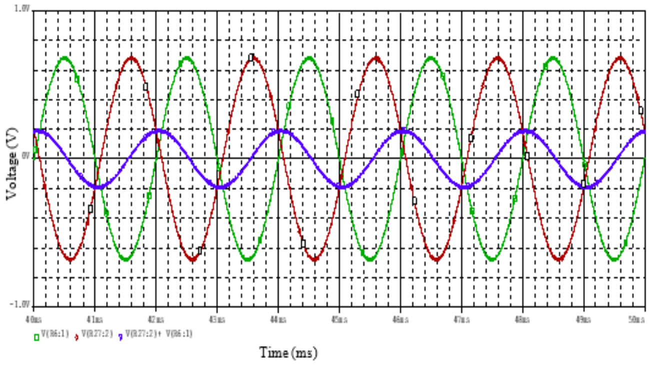

Fig. 7. Sum of Input Signal and Output Signal (500Hz)

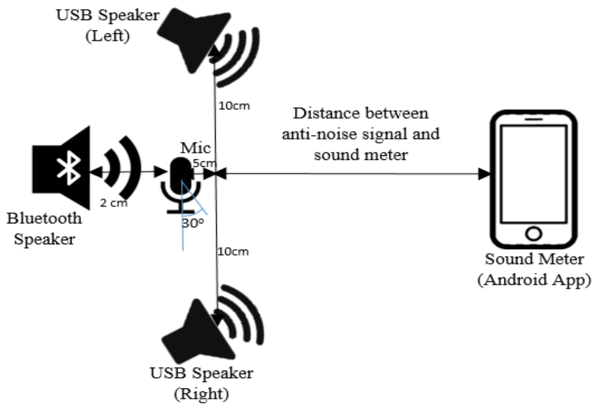

Fig. 8. The experiment Setup for the ANC system

3.1. Single-tone Noise Reduction

In this section, a sinusoidal wave cancellation is examined. The experiment is carried out in a room. The sinusoidal noise is acted as the noise signal and is played through a Bluetooth speaker. The anti-noise signal is generated by the circuit shown in Figure 2 and emitted through a USB speaker. The experiment setup is shown in Figure 8. The experiment is carried out by changing the distance between the microphone and the sound meter, from 5cm to 50cm with an increment step of 5cm. The testing frequency range is started from 100Hz to 500Hz with the frequency step of 100Hz.

3.2. Noise Cancellation in Car

In this section, the noise cancellation in a car is examined. The experiment is carried out in the same room as experiment 1. However, this time the noise in the car is pre-recorded using a smartphone. The experiment setup is shown in Figure 8. Figure 9 shows the measured results of the noise reduction at the different distances between the microphone and the sound meter.

a. 100Hz: The noise reduction is maximum at 20cm, which is 2.4dB. However, the noise reduction only happens at 5cm to 40cm, it starts to amplify at 45cm and 50cm.

b. 200Hz: The ANC system obtained the best performance at 200Hz. The noise reduction is between 4.8dB to 16.7dB. The 16.7dB of noise reduction was achieved at 20cm.

c. 300Hz: For 10cm to 35cm, the noise cancellation is between 1.1dB to 5.4dB. it reached maximum noise reduction at 20cm, which is 5.4dB of noise cancellation. There is noise amplification that happens at 5cm, 40cm, 45cm, and 50cm.

d. 400Hz: 400Hz has the least noise cancellation among the frequencies tested, which is between 0.5dB to 1.8dB. The 1.8dB noise cancellation occurred at 25cm. The noise is amplified at 5cm, 45cm, and 50cm.

e. 500Hz: The noise reduction at 500Hz is between 1dB to 4.1dB. At 20cm, the noise is reduced by 4.1dB. However, it has noise amplification at 5cm, 40cm, 45cm, and 50cm.

The single-tone noise cancellation for 100Hz to 500Hz at 20cm is shown in Figure 10. Conclusively, the ANC system can perform noise cancellation when the distance between the microphone and the sound level meter is 10cm-35cm. The ANC system has optimum noise cancellation when the microphone and the sound level meter (receiver) are 20cm apart from each other.

Figure 11 shows the results of noise cancellation in the car. The results in Figure 11 are taken when the distance between the anti-noise signal and Sound Meter is located 20cm apart. This is because the previous experiment shows that the ANC system proposed achieved the best performance at a distance of 20cm. The signal without the ANC system is represented in blue whereas the signal with the ANC system is represented in orange. The noise at 200Hz has the most obvious cancellation. It has been reduced from ~50dB to ~30dB. The noise at 100Hz is slightly reduced. The noise cancellation for 300Hz-500Hz is not obvious and somehow there is some amplification occurred. The noise at 600Hz and above has been slightly reduced. The total noise level is reduced from 58.4dB to 53.8dB, meaning that the total attenuation is 4.6dB.

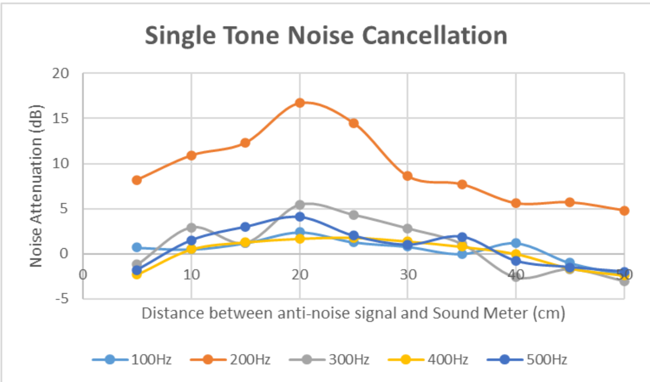

Fig. 9. The results of Single-Tone Noise Cancellation

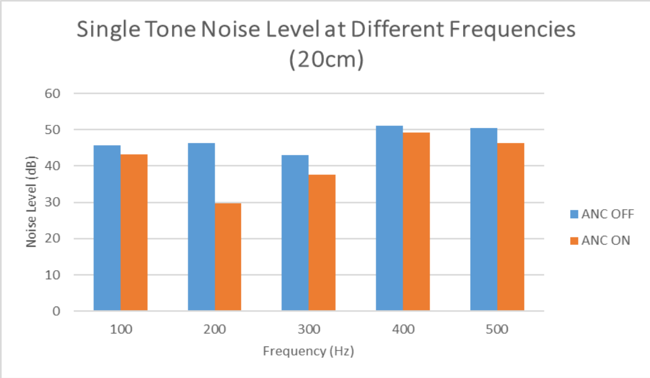

Fig. 10. The results of Single-Tone Noise Levels at Different Frequencies (20cm)

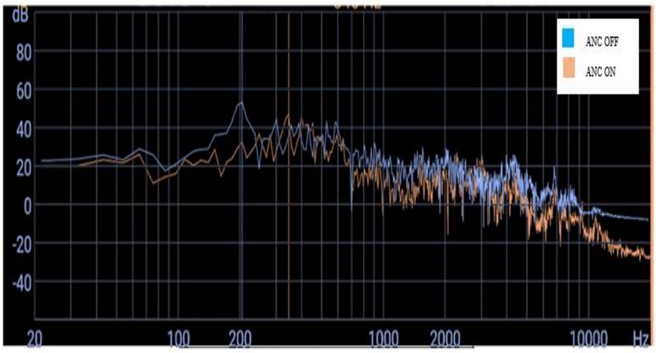

Fig. 11. The results of Noise Cancellation in the Car (20cm)

3.3. Discussion

The noise cancellation by the ANC system for single-tone noise is worked satisfactorily, and it can reduce the noise in the car. The analog ANC system is tested by observing the noise cancellation performance of single-tone noise and noise in the car. The noise reduction achieved for single-tone noise of 100Hz-500Hz (with a frequency step of 100Hz) is 1.7dB (400Hz) to 16.7dB (200Hz). The power consumption of the ANC system is only 248.4mW. This indicates that the system can last for 18.12 hours with a 9V battery. Although the results are still accepted, the output of the ANC system is not as perfect as what has been simulated. The reasons for the imperfection are phase mismatch, the position of the USB speaker, and environmental noise.

Theoretically, the noise signal can be cancelled by the anti-noise signal which is 180o out of phase but equal in amplitude and frequency with respect to the noise signal. The destructive interference performs most effectively when the phase of the two signals is exactly aligned with each other. However, the ANC system's circuit has included the low-pass filter for eliminating the high-frequency noise in the circuit that has caused the lagging of the anti-noise signal. Moreover, the all-pass fill introduced the phase leading to compensate for the phase lag brings by the low-pass filter. The phase mismatch (phase lead and lag) makes the noise signal and anti-noise signal does not match with each other. As a result, in this project, the anti-noise signal generated by the USB speaker failed to be a signal that can perfectly match the phase of the noise signal. Therefore, the results show only partial cancellation at a particular point.

It is also observed that the position of the USB speaker plays an important role in the ANC system. When the placement of the speaker is changing, the output of the noise cancellation will be different. The ANC system is most effective when the USB speaker position in Figure 8 and the distance between the microphone and the receiver (sound level meter) is 20cm. The position of the USB speaker is important because the sound wave travels at the speed of sound which is about 343m/s in dry air at room temperature. Electrical signal travel at the speed of light which is about 3x108 m/s. This means that the noise travels with the speed of sound when it travels from the surroundings to the ears. However, when the noise signal enters the circuit it travels at the speed of light. Then, when the signal emits from the USB speaker back to the environment it travels with the speed of sound. This makes the phase mismatch more serious. Hence, it is difficult or impossible to find a position where the anti-noise signal can exactly match the noise signal.

Besides, the imperfect cancellation is affected by the environmental noise in the experiment room. The experiment is carried out in a room that is enclosed with some other unavoidable environmental noise such as air condition noise, object movement, fan noise, etc. This causes the noise signal is not only desire noise to be tested, which indirectly affects the results. Besides, when tested in the car, there is environmental noise such as the noise caused by the passed by vehicles.

The noise cancellation is the highest and most obvious at 200Hz. This proves that the anti-noise signal matches the noise signal the most at 200Hz. This is because in designing the all-pass filter, 200Hz is taken as the reference point whereby the phase lead in the all-pass is equal to the lag in the low-pass filter. The noise level in the car is highest at 200Hz which caused 200Hz is used as the reference in the design. Therefore, the all-pass filter can compensate for the phase lag caused low-pass filter at 200Hz. However, for other frequency ranges, the phase mismatch is still there, and thus the noise cancellation is less.

Table 2 show the performance comparison of the ANC system proposed with the existing systems. The analog ANC system is proposed in [3] and [9], [9] has better performance than [3]. The system proposed in [9] can reduce 3dB-15dB of noise at 63Hz-1000Hz whereas [3] can reduce 2dB-5dB of noise at 250Hz-1500Hz. Digital ANC system is proposed in [6], [7], [8]. They have average noise cancellation of 9.76dB-15.11dB. The proposed ANC system has an attenuation of 1.7dB to 16.7dB of noise at 100Hz to 500Hz which is comparable to [3] and [9].

Additionally, the overall cost for the proposed ANC system only costs 16 USD. Therefore, the cost of the ANC system proposed is much cheaper than others as it does not require any microcontroller or DSP development board which has a relatively higher cost and is unaffordable for the public. Generally, the proposed ANC system is an affordable choice for the public with a satisfactory noise cancellation performance.

Table 2. The performance comparison of the ANC system proposed with the existing systems.

Item / Related Works	Frequency Range (Hz)	Noise Cancellation (dB)
[3]	250-1500	2-5
[6]	100-1000	7.51-10.14
[7]	200-300	4.6-11.4
[8]	200-700	17.17-23.8
[9]	63-1000	3-15
ANC System proposed	100-500	1.7-16.7

4. Conclusion

This paper presents the theoretical consideration, the design scheme, and the noise cancellation effect of the ANC system for the automobile. The analog ANC system demonstrated a low-frequency noise cancellation with reasonable noise cancellation. It can perform a maximum noise reduction of 16.7dB at 200Hz. At 100Hz, the noise reduction is 2.4dB. The noise reduction is 1.7-5.4dB at 300-500Hz. This ANC system is relatively low-cost compared to [6-8] and it is portable. Therefore, it is affordable, and it could be an alternative to adopt the ANC system in the automobile to reduce noise. In conclusion, the driving experience is improved and becomes quieter and more comfortable with a low-cost and portable analog ANC system for the automobile.

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Author contributions

Wai Leong Pang: Conceptualization, Methodology, Software, Writing-Reviewing and Editing **Kah Yoong Chan:** Data curation, Writing-Original draft preparation **Gwo Chin Chung:** Software, Validation **Florence Choong:** Visualization, Writing-Reviewing and Editing **Pek Ling Wong:** Field study, Visualization, Investigation

Conflicts of interest

The authors declare no conflicts of interest.

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