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Tunable active noise control circuit topology for multiple-feature applications

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A tunable active-noise-control (ANC) circuit topology for headsets used in different applications is presented in this article. In the current consumer headset market, ANC is a mature technology that is commonly applied to wireless headsets connected to smartphones for listening to music and making phone calls. The development of ANC headsets has resulted in low-cost and simple devices due to the built-in ANC registers in the digital circuit. Digital circuit implementation is important to provide ultra-low latency processing for different algorithms compared with using digital signal processors (DSPs). However, a limitation associated with these built-in ANC filters is that the ANC digital circuit has been designed only for the wireless headset consumer market. Consequently, ANC headsets can only be used for designated features. ANC tuned for planes by eliminating low-frequency engine noise has been commonly used in the past twenty years. Pass-through (PT) amplification is also commonly tuned to allow users to hear external sounds and have conversations without having to remove their headset. In addition, ANC and PT amplification are also not allowed to operate simultaneously on the existing chipsets. In this paper, an ANC circuit topology with ultra-low latency processing is presented, where the ANC response of the headset can be tuned without any restriction imposed by the built-in ANC filters. The proposed ANC circuit topology consists of a commercial ANC chipset with an external audio codec to provide tunable characteristics. It is achieved by fixed maximum noise cancellation of ANC chipset being modified by summing with the signal from audio-codec path via an audio mixer. Acoustic performance for several headset applications implemented using the proposed circuit is validated. This simple circuit topology can be easily developed and adapted to the current headset consumer market for consumer-selective ANC in different environments.

Bluetooth classic[1] enables wireless audio streaming and has become the standard radio protocol behind wireless speakers, headsets, and in-car entertainment systems. Bluetooth[2,3] headsets are available in various forms, including earbuds and headphones with different features, such as active noise control (ANC)[4–6], speech enhancement[7,8], and heart rate extraction[9,10], to serve different consumer preferences. The ANC technique can block any external noise, thus providing an improved audio experience for users. Earcups provide traditional passive noise control (PNC), which is one of the environmental noise reduction techniques[11]. In PNC, headsets isolate the surrounding noise using a mechanical design such as in-ear rubber tips or headphone cushions. The PNC technique has been adopted and improved to provide an improved listening environment for users. However, PNC achieves good performance only at high audio frequencies (2–20 kHz). Low-frequency noise (50–2 kHz), such as the engine sound of vehicles or planes, is still perceived by the human ear. Therefore, ANC is important for reducing low-frequency noise in consumer headphones.

The fashion of Bluetooth headsets has made consumers willing to pay for various headset features and styles, which has made the audio industry a huge market. Therefore, manufacturers have invested considerably in research and development in the past years[12]. The development of ANC headsets has resulted in low-cost and simple devices due to the built-in ANC registers in the digital circuit. As a result, ANC fabricated in digital circuits has become a mature and low-cost technology integrated into a single Bluetooth chip solution[13]. Thus, a digital ANC circuit is typically implemented in hardware with in-built registers[14]. This impedes the ability of the headset developers to develop a headset for specific applications, such as sleep quality improvement[15,16], the noise control strategy for autistic individuals[17,18] and enhancing acoustic perception for workers in open-plan

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offices[19,20]. The currently available ANC headsets can only be used for specific features, such as ANC designed for airplanes by removing low-frequency engine noise or pass-through (PT) amplification to enable users to hear external sounds without removing their headset. The typical design goal of the currently available ANC headsets is to eliminate the residual noise that enters the earcup to reduce the overall noise level perceived by the user[21]. However, if the design goal requires a certain amount of residual noise with a specific spectral shape[22,23], the filter has to be tuned again with the new rating metrics taken into account so that it can match the response requirement. This makes it difficult for a headset to serve applications with different desired performance. In addition, existing ANC chipsets do not support simultaneous operation of ANC and PT amplification owing to cost reductions and lack of applications in the consumer market for general users[24,25].

In this paper, an ANC circuit topology is proposed that consists of a commercial ANC chipset with an external audio codec to achieve tunable characteristics for dedicated applications. This is a simple and low-cost circuit topology without any large investment in new chipset development for a small market. It allows ANC and PT amplification to operate simultaneously. Further, this proposed tunable ANC circuitry can be easily developed and implemented in any ANC chipset to serve the existing headset consumer market for consumer-selective ANC in different environments. The background information of digital ANC technology and contributions in this paper are discussed in Sect. "Digital ANC technology and its consideration". The proposed topology is described in Sect. "Tunable ANC circuit topology" and its implementation is presented in Sect. "Implementation and measurement results". The fabricated circuit and the product are also presented in Sect. "Implementation and measurement results". Finally, Sect. "Conclusion" concludes its potential applications and contributions.

Digital ANC technology and its consideration

Figure 1 shows the basic ANC principle. ANC is based on the principle of superposition to cancel noise. According to this principle, an antinoise signal with identical amplitude but opposite phase with respect to the original noise signal is generated, thus canceling the original noise signal reaching the human ear. The digital ANC technique has become the primary solution compared with the analog ANC technique. The digital ANC technique has two approaches, including the ANC algorithm running in DSPs or digital circuits, which can be represented by software or hardware. The filtered-x least mean square (FxLMS) algorithm is commonly used in digital ANC to continuously adjust the coefficients of the digital adaptive filters based on the amount of measured noise[14,26]. As shown in Fig. 1, the traveling time (Δt) required for the sound to travel across the headset depends on the frequency and the mechanical form factors of the headset, such as the thickness (x) of the earcup. The speed of sound (v) and latency across the headset can be found by (1) and (2) respectively,

$$\text{Speed of sound in material } = v = \sqrt{(Y/\rho)}, \tag{1}$$

$$\Delta t = x/v. \tag{2}$$

where Y is the Young's modulus and ρ is the density of material.

Figure 2 shows the ANC measurement setup in an anechoic chamber. Head and torso simulators (HATS) are used to provide built-in human-like ear and mouth simulators, which are designed to accurately measure the acoustical performance of an average adult human. Δt can be measured by the setup shown in Fig. 1, and it is typically between 300 and 400 µs for standard consumer headsets. Thus, to address the issue of changing noise signal characteristics and to cancel out noise for real-time applications, adaptive filters with ultra-low latency processing must be constructed[27,28]. For a digital ANC solution to eliminate the constant environmental noise, a microcontroller[5,6] was proposed. Although its latency processing is considerably not suitable and slow for real-time cancellation, it is still capable of predicting the constant environmental noise. To manage the real time with

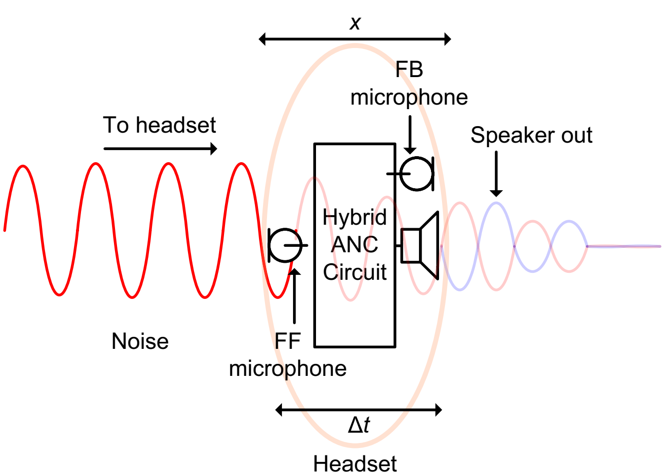


Figure 1. Principle of superposition in the ANC operation.

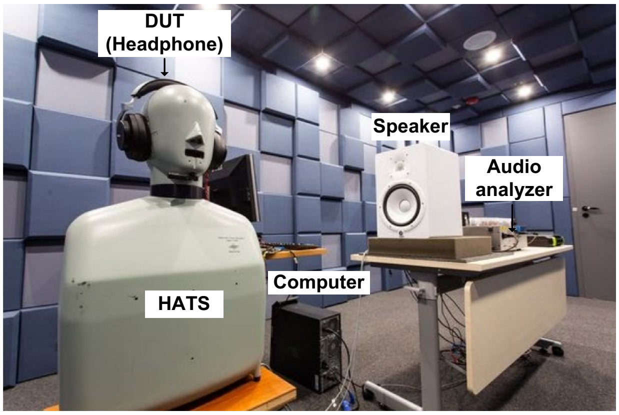


Figure 2. ANC measurement setup in an anechoic chamber.

ultra-low latency processing ANC applications, high-speed and powerful DSPs are required to perform digital ANC, but they are expensive and exhibit high-power dissipation[7,14].

A digital ANC circuit is, therefore, commonly used in headsets since it has ultra-low latency processing, low power consumption and can be integrated with the overall circuits, including the preamplifier (preamp), an analog-to-digital converter (ADC), a digital circuit, a digital-to-analog converter (DAC), an audio mixer, and an audio power amplifier. A digital A field-programmable gate array is used for the implementation of this digital ANC circuit, which is finally implemented in CMOS technology together with other circuits, such as wireless and audio circuits[29,30], in a single chipset. In this way, the overall circuit size and cost can be reduced compared with DSPs. This is because the digital circuit is specifically designed for ANC in commercial market, whereas DSPs are for general use. Figure 3 shows the ANC block diagram of an existing hybrid ANC circuit topology for commercial Bluetooth headset applications. This is a mixed approach that combines feedforward (FF) and feedback (FB) ANC modules, which employ FF and FB filters, respectively. Each module employs FB and FF microphones (mics) pointing to the inside and outside of a headset, respectively, as shown in Fig. 1. Bluetooth A2DP playback enables audio playback from remote Bluetooth-connected devices such as smartphones. The FBC filter shown in Fig. 2 is used for feedback cancellation because the FB mic captures the audio feedback from the speakers.

The setup in Fig. 2 can also be used for ANC development and measurement. The speaker in Fig. 2 generates environmental noise such as pink noise. The FF and FB filters are individually calibrated to obtain the parameters from the target curves. A computer is employed to control the audio analyzer using an automated ANC program for this calibration. Then, the calibrated parameters are loaded into the built-in ANC registers in the digital circuit to implement a hybrid ANC topology. This paper proposes a tunable ANC circuit topology with the following characteristics:

- High flexibility of the tunable performance supporting simultaneous operation of ANC and PT amplification
- It is simple and can be fastly adapted to the existing headphone consumer market for consumer-selective ANC in different environments without any large investment in new chipset development for a small market

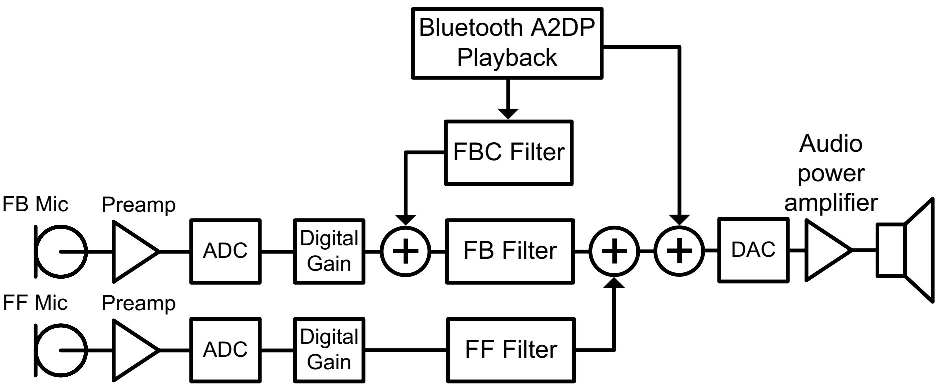


Figure 3. Commercial hybrid ANC circuit block diagram.

Tunable ANC circuit topology

Figure 4 shows the circuit diagram of the proposed ANC circuit. This circuit includes a commercial ANC chipset connected to an external audio codec to overcome the limitation where ANC and PT amplification in existing headset cannot operate concurrently[24,25] and combine their features based on the required acoustic performance. The FF mic is connected to the hybrid ANC circuit and the analog input of the audio codec. The audio codec includes a preamplifier, an ADC, an audio mixer, a DAC, and an audio power amplifier. Normally, the digital circuit in the audio codec has tunable characteristics of digital filtering, equalizing, and automatic level control. The main function of the audio mixer is to combine the audio signals obtained from different paths to form a mixed-signal path since the audio codec has multiple analog and digital input paths. Figure 5 shows the Δt of the headset used to implement the proposed tunable circuit topology. The 1 kHz sound source was used to measure both curves with and without the headset. The difference between blue and red curves is Δt, which is equal to 320 µs. Thus, the total processing time shown in Fig. 4, including the extra delay caused by the ANC path in the audio codec, should be less than 320 µs. In addition, the time required for the mixed-signal path should also be less than 320 µs. The sound signal captured by the FF mic enters the hybrid ANC digital circuit, which performs the ANC operation. The FF-mic signal also enters digital circuit (called the audio-codec path) of the audio codec, which performs signal processing. The audio output from the hybrid ANC digital circuit is normally connected

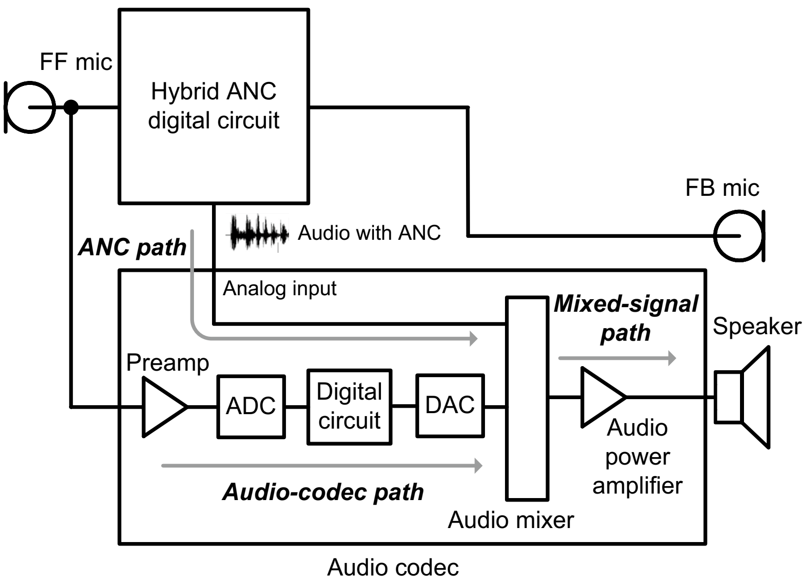


Figure 4. Circuit diagram of the proposed tunable ANC circuit (one side).

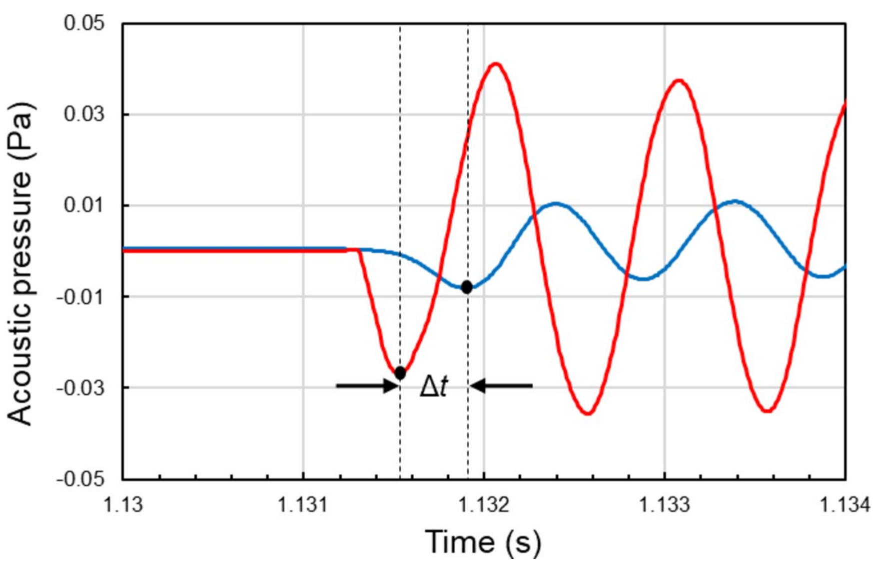


Figure 5. Measured result of Δt: Blue curve is with the headset and red curve is without headset.

to a speaker. In the proposed circuit, it is connected to the analog input of the audio codec (called ANC path). The audio codec in this path performs an antinoise operation with a Bluetooth A2DP playback.

Implementation and measurement results

A commercial evaluation board of the Bluetooth chipset, which employs a hybrid ANC technique, and an audio codec evaluation board were used to implement the headphone shown in Fig. 4. Figure 6 shows the headphone acoustic performance, which includes the frequency response of the original ANC, the ANC-across-the-ANC path, the PNC, the pink noise (without the headphone), and the PT amplification mode. This mode is obtained by turning off the ANC function and using the audio-codec path to capture the environmental sound signals. The roll-off, which starts at 4 kHz, is due to the FF-mic response. The PT amplification mode was implemented by adding gain to the preamp and using a low-pass filter with a quality factor (Q) of 0.1 and a cut-off frequency of 4000 Hz. The PNC curve shows that PNC reduces the noise above 2 kHz, whereas the ANC-across-the-ANC-path curve shows that the tunable ANC circuit reduces the noise below 2 kHz, thus achieving the best reduction.

Two ANC acoustic curves are shown in Fig. 6. The original ANC (blue) curve shows the acoustic performance, when the audio output in the hybrid ANC digital circuit is connected directly to the speaker; the ANC-across-the-ANC-path (pink) curve shows the acoustic performance of the tunable ANC circuit shown in Fig. 4, when the ANC path is used. The parameters used in the built-in ANC filters are the same in both ANCs. The two ANC acoustic curves are similar because the change in the signal phase across the ANC and mixed-signal paths is below 1° at all frequencies.

Figures 7 and 8 show the tunable ANC performance of ANC modes 0, 1, 2, and 3. The orange curve in Fig. 7 corresponds to ANC mode 0. In this mode, the headphone operates under hybrid ANC in the ANC digital circuit.

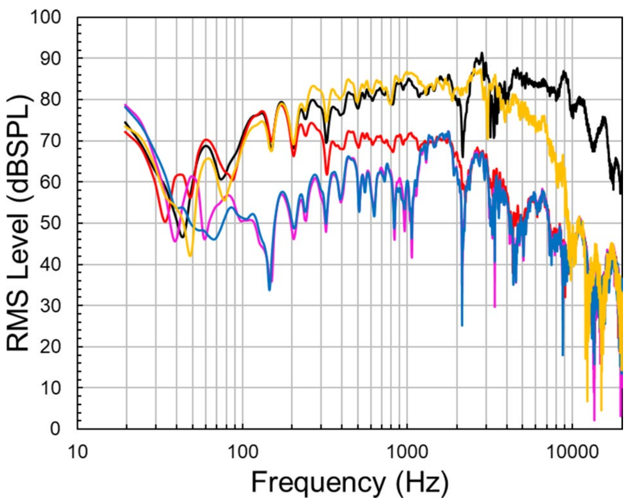


Figure 6. Acoustic performance: original ANC (blue), ANC-across-the-ANC path (pink), PNC (red), PT amplification mode (yellow), and no headset (black).

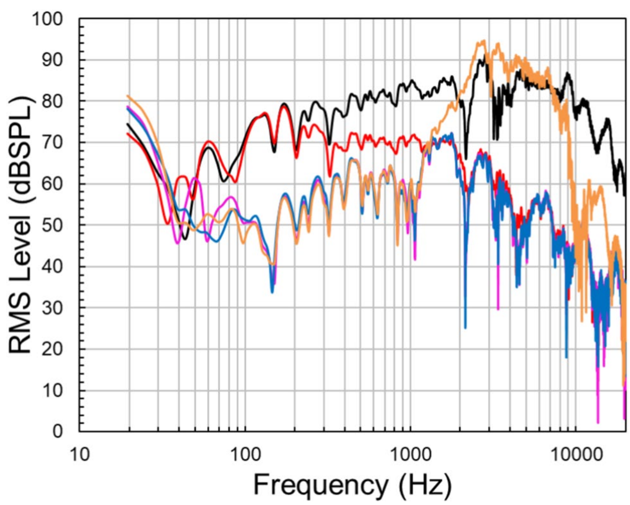


Figure 7. Acoustic performance: ANC mode 0 (orange).

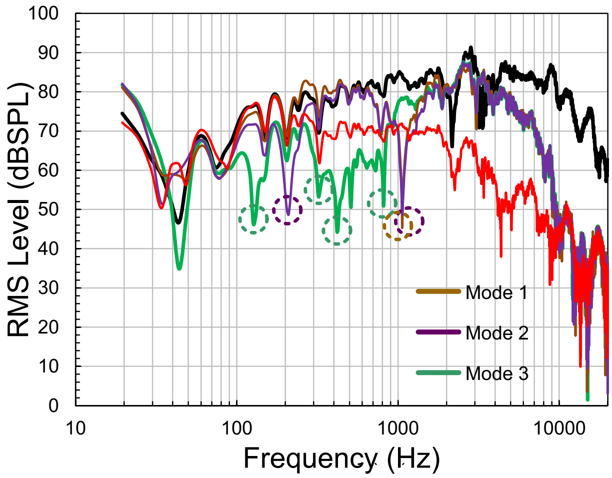
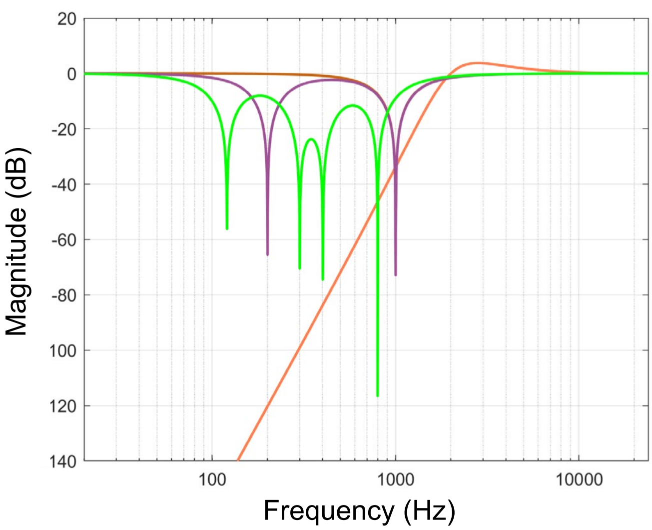


Figure 8. Acoustic performance: ANC mode 1 (brown), mode 2 (purple), and mode 3 (green).

Also, the FF mic captures the environmental sound signal and sends it to the audio-codec path. Therefore, the signal can be tunable to the digital circuit of the audio codec. This mode can be implemented by adding gain to the preamp and using a high-pass filter with Q = 1 and a cut-off frequency of 2000 Hz. This mode can be used for low-frequency noise reduction such as the engine sound of vehicles or planes. However, a high frequency is required to allow user communication, which cannot be implemented in existing ANC headsets. In Fig. 8, different notch filters are used to demonstrate the flexibility of the tunable performance of the proposed circuit. Figure 9 presents the frequency response of the filters for different modes, where all preamps were set to specific gains. In mode 1, a 1000-Hz notch filter was added, whereas in mode 2, another notch filter operating at 200 Hz was added in mode 1. Also, in mode 3, four filters operating at 120 Hz, 300 Hz, 400 Hz, and 800 Hz were added. In Figs. 6, 7 and 8, the same parameters were used in the ANC built-in registers, and the audio codec was used to feedback the environmental sound in the mixed-signal path to implement the tunable operation. Different sets of parameters can be saved in the on-chip memory for different ANC acoustic performances by loading them back into the ANC's built-in registers. Figure 10 shows the difference between PT amplification and PNC of ANC mode 0 and commercial headphones (Solo Pro and Shure Aonic 50). It shows that the commercial headphones do not have any modes that ANC and PT amplification operate simultaneously, which is limited by commercial hardware structure[24,25]. And the proposed topology can be easily developed and adapted to the current headset consumer market for consumer-selective ANC in different environments.

Figure 11 shows the fabricated circuit shown in Fig. 4, which comprises two audio codecs for left and right channels, a Bluetooth chipset supporting hybrid ANC, and the power management circuit. Using the same headset as in the previous section, this fabricated circuit was installed in the headset shown in Fig. 11. To meet varied objectives, a wide range of applications have been developed and designed with different ANC responses, as shown in Fig. 12. The commercial ANC mode (pink color) was mainly designed to reduce low-frequency engine



Color	Mode	Filter	Frequencies (Hz)
(red)	0	High-pass	2000
(brown)	1	Notch	1000
(purple)	2	Notch	200, 1000
(green)	3	Notch	120, 300, 400, 800

Figure 9. Frequency response of filters in different ANC modes.

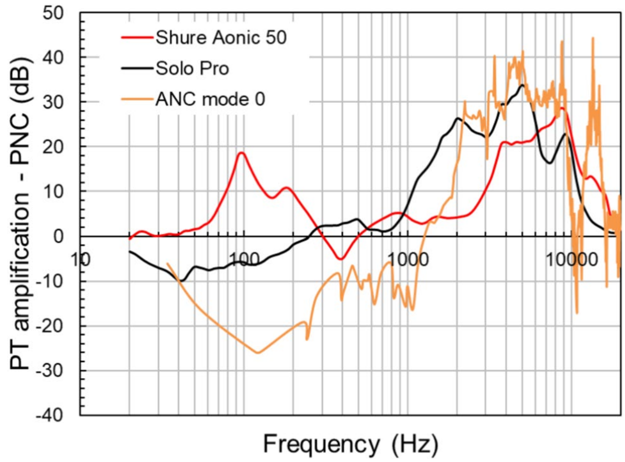


Figure 10. Comparison between ANC mode 0 and other headphones with PT amplification.

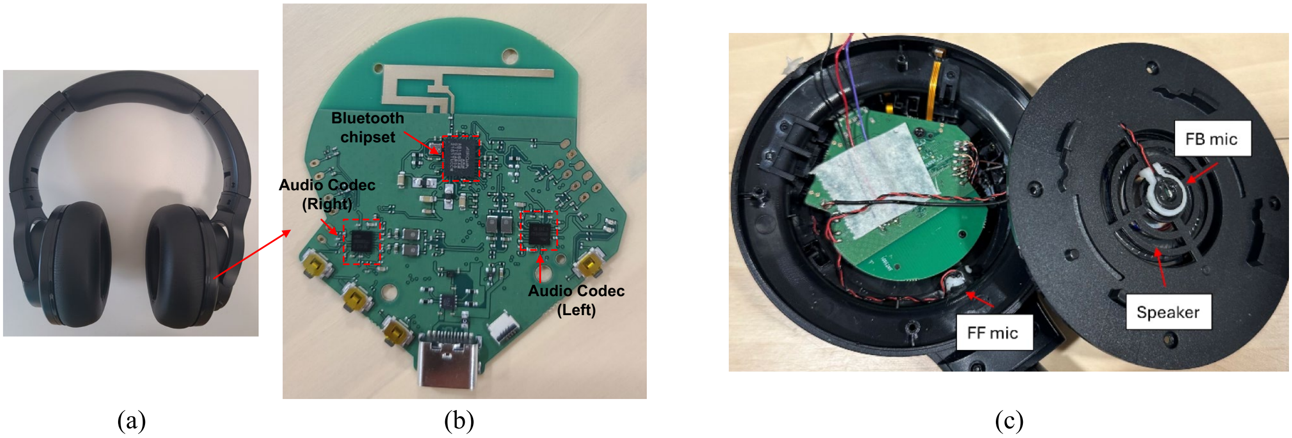


Figure 11. Fabricated tunable ANC circuit in the headset: (**a**) Outlook of headphone, (**b**) fabricated circuit in the headphone, and (**c**) major components and the wire connections to the circuit.

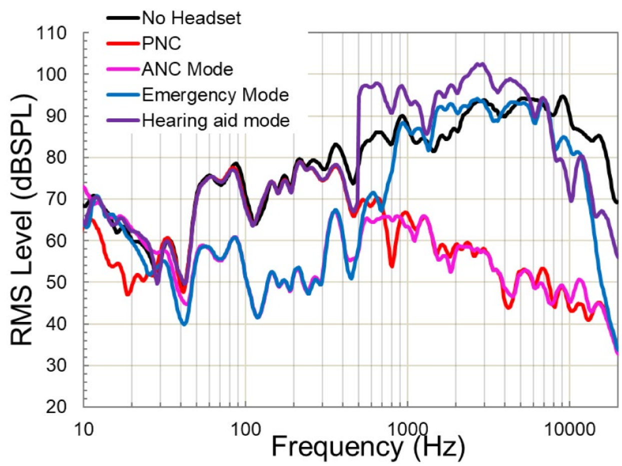


Figure 12. Acoustic performance for different-feature applications.

noise efficiently, with a focus on attaining optimal performance in this area. Due to their high-frequency range degrading first, the hearing aid mode (purple color) was developed specifically for the elderly[31]. The audio codecs on each side can thus be tailored to the specific requirements of each ear. The emergency mode (blue color) is particularly useful in disaster response situations, industrial settings with heavy machinery, or transportation hubs with loud engines and equipment, where low-frequency noise is present and the ability to detect human voices is crucial. Finally, the ASD mode can be employed to meet the specific requirements of individuals with autism spectrum disorder (ASD), who frequently require noise reduction to aid in their sensory processing[16,17]. This response can be modified to provide the specific response required to support individuals with ASD. Due to its flexibility, it is an ideal tool to meet the diverse demands of individuals with ASD. Therefore, different ANC operations can be performed using different sets of ANC parameters and combining different features in the audio codec to achieve multiple-feature applications.

Conclusion

In this article, a tunable ANC circuit topology for different headset applications is proposed. The proposed circuit topology overcomes the existing ANC problem in consumer headsets, where ANC and PT amplification are not allowed to operate simultaneously. By integrating the external audio codec with ANC chipset for additional tuning of acoustic performance, the tuning process of the ANC filter is more straightforward since it is shown in the experimental result that the acoustic performance of tuning with the external audio codec is the sum of filter response from ANC chipset and the external audio codec. Thus, instead of adjusting filter coefficients in the ANC chipset, similar performance can be achieved by setting digital filters in the external audio codec according to the target noise reduction frequencies. Therefore, the proposed circuit topology achieves tunable characteristics in dedicated applications. Also, it is simple and can be adapted to the existing headphone consumer market for consumer-selective ANC in different environments. In the current study, the tunable feature of the proposed circuit is implemented offline with known desired spectral response and the end user cannot fine tune the acoustic performance or create a new sound profile when there hearing needs changed over time. In the future work, it might be beneficial to design and implement a real time tuning platform for the proposed circuit to make it more versatile for the users and enable a more flexible personalization of ANC modes that can account for changing needs and deviation in desired performance in the tuning environment and the actual environment when using the ANC mode.

Data availability

The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

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Author contributions

All authors contributed to the study conception and design. Tak Chun Kwong: Methodology, Software, Investigation, Formal Analysis, Writing. Yat Sze Choy: Methodology, Investigation, Visualization. Chetwyn Che Hin Chan: Investigation, Writing. Steve W. Y. Mung: Hardware, Investigation, Resources, Funding Acquisition, Supervision. Tak Chun Kwong and Yat Sze Choy contributed equally to the manuscript and share first authorship.

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Competing interests

The authors declare no competing interests.

Additional information

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