Recent Technological Advances in Spatial Active Noise Control Systems

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ABSTRACT

This article provides a broad overview of the recent advances in the field of active noise control techniques to reduce unwanted noise over a certain spatial region of interest. Thanks to commercial and technological advances in local active noise control systems extending the size of the quiet zone seems to be a crucial step to developing the next generation of active control systems for a more personalized and quieter audio product. In this review article, the advances over the past decade the in design and development of spatial active noise control techniques to enlarge the controlled sound zone is reviewed. The focus is specifically on the adaptive control techniques and the methods proposed in the frequency domain to control the sound field. The study has paid specific attention to the most important performance measures in designing a spatial active noise control system such as convergence rate, stability and robustness of the algorithm, the size of the quiet zone and how it can be enlarged by configuring the loudspeaker and microphone array geometries. Finally, the authors will discuss the current and future challenges that should be overcome to improve the effectiveness of the recently proposed methods to expand the silence zone.

Keywords: Filter-x LMS, spatial ANC, multi-zone sound field, multi-channel control methods, wave field synthesis, convex optimization methods.

1. INTRODUCTION

Nowadays, acoustic noise is a popular disturbance throughout our life, which increases because of growing industrial equipment in living sites, workplace or even inside a car. Excessive amounts of acoustic noise not only can cause some mental or physical diseases such as hearing loss or headache, but also will be an important factor of distraction and make us exhausted. To reduce unwanted noise, various local and global active noise control (ANC) strategies [1-3, 21] and algorithms have been proposed by researchers over the past decades [4, 5, 22]. In the ANC system, the noise to be cancelled is called ‘primary noise’ and the system uses ‘secondary sound sources’ to generate ‘anti-noise signals’ to reduce the primary noise. The residual difference between these two components is

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measured using a microphone(s) placed inside the cabin and is minimized using a feedforward/feedback control system by considering the principle of destructive interference. Facing the system to time-varying characteristics of sounds, some well-known adaptive algorithms are appropriate for these systems. Due to the demand for the generation of quiet zones in spacious areas contrasting to sound zones as strong as possible, the spatial active noise control systems (spatial ANC) are introduced. Compare to the binaural reproduction ANC systems that are employed in advanced headphones, spatial ANC systems have the capability of control larger conventionally continuous three-dimensional environments. Through design of these systems that benefit linear, and/or two or three-dimensional arrays of loudspeakers and microphones, modeling of the interior environment, developing the ANC algorithm, and improving the proposed algorithm to achieve more efficiency are considered. Thanks to developments of technology, a wide variety of domestic and industrial applications that benefit these systems are introduced commercially from creating multiple quiet and sound filled zones at home to generating a calm workplace. In this paper, some applications of the spatial ANC systems will introduce. Therefore, the main approaches to design the spatial ANC systems and enlarging the region of interest will review. Finally, in the fourth section, the current challenges will be discussed and the future works are mentioned.

2. COMMERCIAL EXPLOITATION

Thanks to the state-of-the-art spatial active noise control, the feeling of immersion and full perception of the auditory environment is achieved for listeners. The spatial ANC systems are designed by employing efficient adaptive controllers and synchronizing different types of microphones and loudspeakers that are selected in terms of the requirements of the specific usage. Compare to primary reproduction systems such as the Binaural technique, the spatial ANC systems relax the limitation of movement in the controlled regions and individual reproduction systems. Moreover, due to the ability of localization and auralisation of the sound events, many companies commercialized the spatial sound systems that would be used not only in the industry but also in non-industrial usage; however, research on the improvement of the efficiency of spatial ANC systems in both commercial and technical fields in terms of generating higher performance and lower cost have been increasing rapidly. Here we review just a few more important real-life potential applications of spatial active noise control.

2.1. Quiet Workplace

Due to working industrial machinery, operation of air-conditioning, and talking employees the workplaces are a complete noisy area. Noise reduction in these environments leads to a decrease the distraction factors, psychological effects, and an increase in the efficiency of employees. In this regard, the ANC system introduced by the Silentium proposes the ‘’Quiet Bubble’’ technology to create a quiet zone around the person[1]. Moreover, sound masking systems are introduced to decrease the background noise in offices and other areas. In this method, the speakers are mounted under the ceiling over each desk or zones to create masking signals[2].

2.2. Personalized Sound Zone

The multi-zone reproduction technique is a state-of-the-art technology that is introduced recently. Due to this method, the general target area can be divided into some regions with different levels of sound or silence. The different array of loudspeakers and microphones contribute to reproducing various levels of sound signals and anti-noise signals individually in terms of reproducing the desired sound and noise reduction. In commercial class, some multi-zone systems are introduced to generate different levels of music or paging for each zona separately. These systems are proper for restaurants, offices, hospitals, conference rooms, schools, and other public or private halls.

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[1] https://www.silentium.com/technology-2/quiet-bubble/

[2] https://www.softdb.com/sound-masking/

2.3. Quiet Car Cabins

Today, automakers and researchers attempt to reduce the noise signals inside the cabin of cars. In this regard, quiet cabins are offered by auto factories, and spatial active noise control is introduced by auto factories and research companies. Hyundai Motor Group is the first company that designed an active noise control to reduce the road noise as the louder noise in the cabin of Hyundai Palisade and Kia K9 car models[1]. The cabin of Mercedes Benz-Maybach S-class sedans is equipped with a road noise active compensator and surrounded by a 4D surround sound system[2]. Some other cars as Jaguar F-Pace, Jaguar XF sedan, Range Rover Velar[3] are also equipped with active noise control systems and further research and development are underway by some other companies such as HERMAN to develop new techniques to cancel the spatial noise inside the cabin of cars efficiently[4].

3. Control Method

Spatial ANC systems try to replicate a complete acoustic environment or synthesize convincing new ones [6] using multiple microphones and loudspeakers. In this regard, sound recording, and sound reproduction are two significant aspects of the spatial audio, where not only the audio content, but also the spatial properties of the sound source/acoustic environment are preserved and reproduced to create an immersive experience. In the following section, the main control methods that are used in spatial ANC systems will be reviewed.

3.1. Spatial Sound Field and Multi-Zone Technique

In convention spatial ANC systems, error microphones are mounted on the boundary of the target area and loudspeakers outside of it. To relax this limitation, using one or multiple circular arrays instead of a spherical one is investigated. The proposed method in [7] reproduces 3-dimensional multi-zone sound field by a circular loudspeaker array. This method increases the performance of the system in a larger spatial area and also decreases the number of loudspeakers by using lower-order spherical harmonics compared to the conventional acoustic contrast control (ACC) method. In [8] a 2.5-dimension multi-zone area is reproduced by a circular loudspeakers array; however, the effects of the head and body of the listener are modelled as a rigid sphere in the bright zone. The proposed model improves the performance of the systems facing broadband frequency and a wide variety of angles. Besides, the topology of loudspeakers and microphone arrays are investigated besides spatial ANC strategy. Physically, the regular array has its limitation and it could be relaxed by using irregular ones. In [9], the multi-sweet spots are reproduced by an irregular loudspeakers array that benefits the intensity matching technique.

In [10], a multi-zone is created by using just one loudspeakers array in a very simple and flexible way. The study proposes two methods to configure the loudspeaker array, i.e. the continuous loudspeaker method and the Least Square method; the results show that both methods demonstrate reasonable performance. The method is applied to a reverberant room by calculating the coefficients of the room response to each loudspeaker. The diffraction effects are also considered in the result.

3.2. Personal Sound Zone and Sound Zone Optimization

The improved technique to create the personal sound zone called Weighted Pressure Matching with Sub-Band Decomposition (wPMSD) is introduced instead of using a broadband filter for loudspeakers [11]. The proposed method benefits from the optimization of each individual sub-band filter in a Generalized Discrete Fourier Transform (GDFT) filter bank. It is shown that using this method leads to achieving lower computational complexity than the wPM in the time domain, and more flexibility in setting the loudspeakers and filter length than the conventional wPM method.

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[1] https://www.caranddriver.com/research/a31608803/quietest-cars/

[2] https://group-media.mercedes-benz.com/marsMediaSite/en/instance/ko/Even-quieter-thanks-to-sound-wave

[3] https://media.jaguarlandrover.com/news/2020/10/new-jaguar-land-rover-noise-cancellation-tech-helps-reduce-driver-fatigue

[4] https://www.halosonic.co.uk/

In [12], a sound field reproduction technique by reducing the leakage in the dark zone is considered. The proposed method attempts to reshape the resulted imperfections in the inaudible range using the variable span linear filter (VSLF) technique. The results show that the performance of the proposed method is constant through the acoustic contrast (AC), the short-time objective intelligibility (STOI), the normalized signal distortion (DSP), the instantaneous perceptual similarity (PSM), and the target-to-interferer ratio (TIR) criteria, imply the efficiency of the method in terms of reproduction performance. Moreover, the Multi Stimuli with Hidden Reference and Anchor (MUSHRA) listen tests show that the proposed perceptually optimized sound zones would have around 20% better performance than other methods.

3.3. Room Reverberation Modeling and Image Source Method

To minimize the summation of the squared errors relating to each zone, the steepest descent algorithm is employed through the control of a multi-zone area by the multichannel filter-x least mean square (MFxLMS) technique in [13]. Moreover, the reverberations of the walls are modelled by the image source method (ISM). The results show that by increasing the quantity of the secondary sources, the feasible system improves the performance of the noise reduction and the convergence rate; however, increasing the weight leads to improving the performance of noise reduction.

In [14], an angular power distribution method is used to model the reverberation of the room. The modelling benefits from the von Mises-Fisher mixture function (vMF). The achieved estimated vMF data is transformed into directional power vectors in the spherical harmonic domain. The simplicity of the proposed modelling leads to analyzing the directional features of the reverberations using the achieved data.

3.4. Wave-Domain Sound Representation Approach

The wave-domain sound field representation and active room compensation to control the sound pressure over the target area are introduced as a new multi-zone creation instead of the conventional point-to-point approach. Using the directional loudspeakers leads to enlarging the control area and decreases the number of required loudspeakers.

The wave-domain adaptive filtering (WDAF) approach transforms the signals at the microphones and the loudspeaker signals into the wave-domain and then adaptively calculates the loudspeaker compensations signals. Two new adaptive algorithms, zero attracting multipoint complex FxLMS (ZA-MP-CFxLMS), and zero attracting wave-domain complex FxLMS (ZA-WD-CFxLMS) are introduced in [15]. The mentioned techniques benefit from adding the constraint on the weights of loudspeakers. The results show that using the ZA-MP-CFxLMS technique leads to more efficient adaptive performance than the conventional multichannel method when we are facing with the sparse distribution of noise sources. In [7], the wave-domain acoustic contrast control (WD-ACC) method is proposed by employing the circular loudspeaker array over three 3D spaces. The simulation results show that the WD-ACC demonstrates better performance with a fewer number of microphones than the conventional ACC in terms of the average acoustic contrast technique over the desired multi-zone region.

3.5. Modal Domain Sound Representation and Sparseness Approach

The modal-domain approach is used to reproduce the anti-noise signal through some independent zones and relies on the spatial harmonic expansion using the Lagrange cost function. In [16], a tuning algorithm for reproduction performance between the dark and bright zones is introduced. The proposed method benefits from two Lagrange multipliers to control the interference between the sound zones and leakage outside the zones. The Simulation results state that two Lagrangian multipliers can be used to tune the performance of the bright and dark zones.

The proposed method in [17] benefits from both weighted sparse plane wave and compressive signal approaches to attenuate the spatial aliasing artifacts caused by the spatial sampling through the noise recording. In this method, the model coefficients of the reference signal are used instead of using the extracted direct mode coefficient which is affected by the spatial aliasing. In the optimization stage, the Iteratively Reweighted Least Squares (IRLS) is introduced here due to its fast convergence of the iteration numbers. Then the mode weights are updated using the normalized least mean square filtered-x (Fx-NLMS) algorithm. The results show that the proposed algorithm not only decreases the noise more effectively, but also makes quicker convergence beyond the spatial Nyquist frequency.

3.6. Virtual Sensing Technique

To move the quiet zone closer to the desired locations, virtual sensing techniques are proposed. In [18], the virtual microphone control (VMC) method is developed for a multichannel ANC system equipped with the virtual sensing (VS-MCANC). In this method the sum of the squared primary noise value is minimized at the location of the desired virtual error microphones. To achieve optimal control, the auxiliary filters are trained to calculate the error between the physical and virtual paths. Furthermore, the locations of the physical and virtual error microphones are independent in the virtual sensing multi-channel ANC (VS-MCANC) method. The results demonstrate that at the virtual microphone locations both conventional and VS-MCANC algorithms have similar reduction levels, however, VS-MCANC algorithm can optimally control the noise at the virtual microphone locations without the spatial correlation and causality distractions.

3.7. Psychoacoustic Approach

Due to the selective sensitivity feature of the human auditory system, some psychoacoustic-based ANC systems are introduced. In [19], a psychoacoustic system is proposed working based on delayless subband adaptive filtering; The psychoacoustic feature used in this method is loudness. The simulation results show an improvement in noise reduction and a decrease in the computational complexity. Moreover, the psychoacoustic technique suggested in [20], shows a comparable result in terms of the performance and computational complexity compared to the ANC systems in which the auditory system of humans are neglected.

4. CONCLUSIONS

In this review paper, further to a brief introduction to spatial active noise control systems, an account of their most important commercial applications is reviewed. By comparing both conventional control methods of the spatial ANC systems, their performance in terms of the noise reduction are compared and the challenges for both are reviewed. The multi-channel control method is a common approach to control the target area. Although using the spherical array of microphones and loudspeakers seems to satisfy the 3D space conditions, multi circular array can relax the limitation of using spherical microphone array to a large extent. Reducing the number of microphones and loudspeakers is resulted from using ANC algorithms in wave-domain or modal domain. Moreover, the implementation of the virtual sensors further to the physical sensors assist to enlarge the region of interest. As the future work, designing appropriate efficient spatial ANC in a significant noisy environment such as car cabin or an open area workplace are anticipated. Finally, it should be noted that any attempt to expand the size of the control zone may degrade the performance of the noise reduction and increase the computational complexity of the algorithm.

REFERENCES

1. A. Montazeri, J. Poshtan, M.H. Kahaei, “Analysis of the global reduction of broadband noise in a telephone kiosk using a MIMO modal ANC system,” International Journal of Engineering Science, vol. 45, no. 2–8, pp. 679-697, 2007.
2. A. Montazeri, J. Poshtan, “GA-based optimization of a MIMO ANC system considering coupling of secondary sources in a telephone kiosk,” Applied Acoustics, vol. 70, no. 7, pp. 945-953, 2009.
3. A. Montazeri, J. Poshtan, ‘Optimizing a Multi-channel ANC System for Broadband Noise Cancellation in a Telephone Kiosk Using Genetic Algorithms,’ pp. 241 – 260, 2009.
4. L. Lu, K-L. Yin, R.C. de Lamare, Z. Zheng, Y. Yu, X. Yang, B. Chen, “A survey on active noise control in the past decade—Part I: Linear systems,” Signal Processing, vol. 183, 2021.
5. A. Montazeri, J. Poshtan, "A Computationally Efficient Adaptive IIR Solution to Active Noise and Vibration Control Systems," IEEE Transactions on Automatic Control, vol. 55, no. 11, pp. 2671-2676, Nov. 2010.

6. W. Zhang, P. N. Samarasinghe, H. Chen, and T. D. Abhayapala, "Surround by sound: A review of spatial audio recording and reproduction," Applied Sciences, vol. 7, no. 5, p. 532, 2017.
7. Z. Han, M. Wu, Q. Zhu, and J. Yang, "Three-dimensional wave-domain acoustic contrast control using a circular loudspeaker array," The Journal of the Acoustical Society of America, vol. 145, no. 6, pp. EL488-EL493, 2019.
8. Zhang, W. Zhang, L. Zhang, and M. Zhu, Active control of scattering effects in 2.5 D multizone reproduction. Universitätsbibliothek der RWTH Aachen, 2019.
9. H. Zuo, P. N. Samarasinghe, and T. D. Abhayapala, "Intensity based spatial soundfield reproduction using an irregular loudspeaker array," IEEE/ACM Transactions on Audio, Speech, and Language Processing, vol. 28, pp. 1356-1369, 2020.
10. Y. J. Wu and T. D. Abhayapala, "Spatial multizone soundfield reproduction: Theory and design," IEEE Transactions on audio, speech, and language processing, vol. 19, no. 6, pp. 1711-1720, 2010.
11. V. Molés-Cases, G. Piñero, M. de Diego, and A. Gonzalez, "Personal sound zones by subband filtering and time domain optimization," IEEE/ACM Transactions on Audio, Speech, and Language Processing, vol. 28, pp. 2684-2696, 2020.
12. T. Lee, J. K. Nielsen, and M. G. Christensen, "Signal-adaptive and perceptually optimized sound zones with variable span trade-off filters," IEEE/ACM Transactions on Audio, Speech, and Language Processing, vol. 28, pp. 2412-2426, 2020.
13. X. Tang, J. Zhang, and T. D. Abhayapala, "Active Noise Control Over Multiple Zones: Adaptive Algorithm in Time Domain," in 2020 Asia-Pacific Signal and Information Processing Association Annual Summit and Conference (APSIPA ASC), 2020, pp. 288-292: IEEE.
14. A. Bastine, T. D. Abhayapala, J. Zhang, and H. Sun, "Modelling Room Reverberation Directivity using von Mises-Fisher Mixture Distribution," in 2020 Asia-Pacific Signal and Information Processing Association Annual Summit and Conference (APSIPA ASC), 2020, pp. 694-700: IEEE.
15. J. Zhangg, T. D. Abhayapala, P. N. Samarasinghe, W. Zhang, and S. Jiang, "Sparse complex FxLMS for active noise cancellation over spatial regions," in 2016 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP), 2016, pp. 524-528: IEEE.
16. W. Zhang, T. D. Abhayapala, T. Betlehem, and F. M. Fazi, "Analysis and control of multi-zone sound field reproduction using modal-domain approach," The Journal of the Acoustical Society of America, vol. 140, no. 3, pp. 2134-2144, 2016.
17. Y. Maeno, Y. Mitsufuji, and T. D. Abhayapala, "Mode domain spatial active noise control using sparse signal representation," in 2018 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP), 2018, pp. 211-215: IEEE.
18. D. Shi, B. Lam, and W.-s. Gan, "Analysis of multichannel virtual sensing active noise control to overcome spatial correlation and causality constraints," in ICASSP 2019-2019 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP), 2019, pp. 8499-8503: IEEE.
19. H. Bao and I. M. Panahi, "Psychoacoustic active noise control based on delayless subband adaptive filtering," in 2010 IEEE International Conference on Acoustics, Speech and Signal Processing, 2010, pp. 341-344: IEEE.
20. V. Belyi and W.-S. Gan, "Psychoacoustic subband active noise control algorithm," in 2017 Asia-Pacific Signal and Information Processing Association Annual Summit and Conference (APSIPA ASC), 2017, pp. 457-463: IEEE.
21. A. Montazeri, J. Poshtan, MH Kahaei, “Modal Analysis for Global Control of Broadband Noise in a Rectangular Enclosure,” Journal of Low Frequency Noise, Vibration and Active Control. 2007;26(2):91-104.
22. A. Montazeri and J. Reger, “Developing an IIR robust adaptive algorithm in the modified Filtered-x RLS form for active noise and vibration control systems,” IEEE Conference on Decision and Control and European Control Conference, 2011, pp. 7994-7999.