International Journal of Computer- Aided Technologies (IJCAx) Vol.13, No.1/2/3, July 2026

ACTIVE NOISE CONTROL: A CASE OF A MATHEMATICAL A-WEIGHTED FILTER EXPERIMENT FOR ROAD TRAFFIC NOISE IN NAIROBI CITY

OCHUNGO Akech Elisha[1&2], OSANO Simpson Nyambane[2], and GICHAGA John Francis[2]

[1]Department of Civil and Construction Engineering, University of Nairobi, P.O. Box 30197-00100, Nairobi, Kenya.
[2]Department of Civil, Faculty of Engineering and Technology (FoET), Multimedia University, P.O. Box 15653- 00503 Nairobi, Kenya.

ABSTRACT

The use of Active Noise Control (ANC) method to attenuate road traffic noise (audible noise produced by vehicle road-tire interaction) is steadily increasing in many cities across the world. It has received praise from scores of scholars due to its inherent advantages over the traditional passive noise abatement methods like barriers and tree canopies. It is claimed that the passive approach is not only capital intensive but is also space demanding. Onboarding ANC system can be in very many forms including use of adaptive smart systems, specially designed noise absorbent pavements, in-car noise control system among many others to cancel produced noise out. The present study has however used a mathematical framework to compute the A- weighted equivalent continuous sound level (Leq) from WAV audio files to propose noise filter strategy that can help in proposing noise-absorbent pavement material to active cancel tire-noise. The method has leveraged the IEC 61672-1 standard for A-weighting filters by loading audio data, converting the same to sound pressure, designing a precise A-weighting filter, segmenting the signal into time windows, applying the filter, and calculating Leq for each segment and the entire signal. This has entailed mathematical derivations, including filter design and sound pressure level computations which has borrowed from recent research works dating from the year 2020. The computational effort has depended heavily on resources from Python libraries including, Librosa, NumPy, SciPy, and Acoustics because of a strong numerical stability and practical applicability. The result show how the approach is novel in transformation of WAV road traffic noise audio files collected from 42 sites across Nairobi city into frequency domains. This has made it possible to identify noise hotspot locations and time of high noise. The identification of high-noise locations can inform change of pavement types into active noise absorber counter-measures. The study recommends for the deployment of smart noise sensors across Nairobi city streets.

KEYWORDS:

Active Noise Control, A-Weighted, equivalent continuous sound level Network Protocols, Wireless Network, Mobile Network, Virus, Worms &Trojon

1. CONTEXT

Controlling road traffic noise using passive methods such as vegetation and concrete barriers has become a widespread practice in urban areas [32]. Notwithstanding its dominance, it has a significant downside economically. Hence the experimentation with active noise control (ANC)

DOI:10.5121/ijcax.2026.13301

techniques [43]. ANC is an old method credited to the person of Paul Lueg from the 1930s [14]. Today, ANC has gained a buzzing commercial success particularly in aviation aircraft cabins [13], automobile cabins [36] and headsets in open office plans [19], all which demonstrate its immeasurable public health and economic benefits [50]. In the audio signal world, several companies have successfully used the ANC technique to generate antinoise that then cancels undesired sounds based on the superposition principle [7].

In the road sub-sector, the in-car noise control began with passive control methods including; structural damping or sound-absorbing materials whose drawbacks are immense [59]. Some of the disadvantages include, increasing the vehicle weight, reducing affordability of cars, and introducing inefficiency at lower frequencies. Because of such weaknesses, the in-car noise control engineering has adopted ANC.For roadside noise, passive noise control approaches like noise barriers and green belts have received widespread policy application. However, they occupy urban space, exacerbating the scarcity and high cost of already congested city areas. This has flung open the door for the entry of ANC method also in the roadside space, since it can address specific frequency ranges [60]. Many scholars have discussed the application of Least Mean Squares (LMS) algorithms to address the in-road traffic noise which are mostly in the mid- to low-frequency range (below 2000 Hz). In real-world settings, one would imagine the use of tunnels in highway noise control as discussed by [62] which borrowed from the working of [42]. Whereas it is recognized that noise from moving vehicles carry unstable signals, scholars have proposed fixed coefficient feedforward ANC system with a pseudo-noise source [38]. This has also seen hybriding of both active and passive noise controls by adding ANC systems onto sound barriers to help cut down the low-frequency noise. In the more complex but dominant source of road noise [34], that is, tire–road noise which continues to excite new smart pavement material research, ANC adoption is receiving praise. The ANC adoption in the road field is spawning especially in the use of small openings (porosity embedment, like use of porous polycarbonate nano-materials) to handle broadband noise [11]. This mirrors its work in the audio world, where use of algorithm-driven adaptive filters that work on the principle of noise cancellation to control noise is on a frenzy [55]. The most common of these algorithm types, is the filtered reference least mean square (FxLMS) algorithm [10], whose slow convergence characteristics have reduced their effectiveness in dealing with dynamic noise sources like those from the road space. Researchers are on expedition to cure this, for example use of Kalman filter with a novel dynamic ANC model is on the rise [61].

Other scholars are using the numerical modeling procedure under free field conditions, aiming for global noise reduction [6]. The ANC method has mostly been used in confined spaces, like in equipment such as compressors, in-cabins and the likes. However, for outdoor, considerable discussions by [44; 23] have spurred great interest. This has seen the groundbreaking work by [5] on ANC for stationary, almost pure-tone, low-frequency noise, such as that produced by electrical transformers and reactors in power and transformation plants. These machineries produce the same kind of noise as that from the mixed-volume road traffic which typically are made up of low frequency (below 250 Hz) especially due to the presence of heavy vehicle engines, exhaust systems and tire-road interaction [48]. This is the motivation towards the production of this research paper whose aim is to design a mathematical A-weighted active noise filter model for Nairobi city's road traffic noise control. The main contribution of this research is the outlining of a simplified mathematical framework for processing WAV audio signal files to compute $L_{eq,A}$, to facilitate the design of an A-weighting filter and the computation of sound pressure levels over segmented windows in the Python Software environment while ensuring robustness and reproducibility. The rest of the paper presents related work, methodology of design, proto-typical results, discussion and conclusion. This work has contributed knowledge by expanding the application of active noise control method in outdoor spaces [63].

2. RELATED WORK

Active techniques for controlling noise have developed very fast towards the 1990s, largely due to advancement in modern electronics. They are fairly inexpensive digital signal processors which have received swifter adoption across disciplines because they are widely available. They enable analog audio frequency signals to be converted into digital form, processed via a digital filter (Kumar,2020), and then converted back into an analog signal with very little time delay. Their inherent electronic capability, alongside the wavey nature of sounds, has made the implementation of active noise control a feasible practical proposition [43]. For a successful noise control, sound pressure level (SPL) of the source need to be measured [40].

Sound pressure level (SPL) is a logarithmic measure of the effective sound pressure of a sound relative to a reference value. To measure SPL, a Sound Level Meter (SLM), an instrument made up of a microphone, a preamplifier, analysers, and a display screen, all packaged as one tool, is used [24]. Before use, it is calibrated as per the International Electrotechnical Commission (IEC) 61672 standard [9]. Excess level of sound is known as noise, a phenomenon which has long been considered as a source of annoyance since antiquity. The World Health Organization recognizes noise as a serious health hazard. Hence the effort towards the control of noise, from source, through the propagation path and at the receiver's station. There are many ways of controlling noises in the environment, key among which, is active noise control (ANC) method which operates by cancelling further propagation [4]. This can be achieved by deploying mathematical approaches [28].

ANC is a noise cancellation typology leveraging the principle of superposition of acoustic signals [29] whose goal is to produce an anti-noise with the similar amplitude and opposite phase of the original (unwanted) noise to cancel or abate its harmful effects [15]. The WHO sets the safe sound level limit for humans using a specified A-weighted equivalent continuous sound level, (LAeq). By definition the A-weighting is a frequency weighting commonly used when assessing the risk of sound-induced hearing injury [49]. It approximates the sensitivity of human hearing to sounds of different frequencies. Cities worldwide, Nairobi included, are a playfield to diverse variety of sounds .To a number of urban residents, the environmental soundscape has conventionally been taken as the sacrifice they must live with in exchange for the convenience associated with living in close proximity to certain locations, for example near busy highways [31].The reason is that, traffic noise is a significant source of noise pollution, which has the tendency of disrupting urban environments with fluctuating sound [46].

Active Noise Control is best explained using the experience borrowed from medical auditory technology field [3]. Just to recall, it is known that, a typical headphone uses an Active Noise cancellation (ANC) system and is the reason they are mostly used in open-office plans [19]. The external microphone of a headphone captures the ambient sound field and the internal microphone captures the sound pressure on the inside of the earcup or ear canal of a listener [30]. The carried signal contains a mixture of any noise that has been transmitted through the headphone and the signal that the user wants to hear. These signals are compared to calculate a delay function which describes how long it takes for the noise to transmit to the interior microphone. By mixing in a delayed, inverted, and scaled copy of the exterior noise signal, the ANC system attempts to cancel out this noise.

Further to the delaying the signal, there may also be adaptive filtering implemented in these systems [15]. Digital filters are commonly used mathematical functions which are used to selectively attenuate or boost frequencies or frequency bands in a signal. Adaptive filtering covers a range of algorithms which are used to estimate a filter to suppress or isolate a signal automatically. Following such cues, adaptive filtering techniques have emerged in different fields for noise control in most technology devices, all using mathematical algorithms [16]. In road safety, different acoustic warning devices are being designed for instance to alert pedestrians by cyclists. Generally, and in order to reflect the changes in soundscapes as internal combustion engines in road cars are phased out, UN regulation 138 [54] is undergoing homogenization into national laws across the world to guide governance and specification of electric car alert sounds. One would be tempted to give accolade on the standardization of alert and warning sounds in the road safety front where signal features associated with increased detection distances are being used in vehicle alert sounds. In this, the amplitude of modulated tones in the range 800 Hz-1 kHz have helped in improving detection of e-scooters [53]. Researchers have continually reported that, environmental sound affects the detectability of vehicle alert sounds. Nonetheless, the detectability of sounds with high frequency components is not significantly impacted on by environmental noise levels [17]. The reason for this is that, the frequency masking effects where tones which are within the spectrum of competing noise are masked due to the frequency response of the inner ear [18]. Where alert sounds are outside the spectrum of interfering noise, detectability is improved. A part from the environmental noise affecting detectability, distraction also has a significant impact on detectability.

In road traffic noisescape, tire–road noise is a major contributor [37]. Further, a lot of research work is ongoing to improve the effectiveness of Active Road Noise Cancellation/Control (ARNC) technology both for the in-cabin and for the external environment (Zoller et al.,2017). To that extent, this study recognizes that sound level measurement is essential in environmental noise assessment (Duhamel et al,1998), occupational health monitoring, urban planning, and audio engineering [22]. This is premised on the fact that, mid-frequency sounds (1-4 kHz) marking the threshold of most sensitive human hearing [47] are the most common residual road noise nuisance to mankind. Hence therefore the call for attenuating low and high frequencies to align with equal-loudness contours [9].

3. METHODOLOGY DESIGN

The research team used Standard Sound Level Meter (SLM) Type 1, calibrated to IEC 61672-3 [1]. It captured sounds of pass by vehicles in 42 locations spread across Nairobi City. The camera was set 1 meter from the road edge and elevated at 1.2m above the ground level. The SLM measured the r.m.s. magnitudes of the weighted electrical counterparts of sound waves. These "effective" magnitudes are the most convenient and perhaps the most fundamental magnitudes to measure since they are associated with the weighted energy in the sound wave through simple and well-known formulae. The captured data was loaded and converted into audio data. Afterwards, the team designed an A-weighting filter mathematically by segmenting the signal [58]. The resulting signal was passed through the filter to compute the L_{eq}. Next sections below is an elaboration of the mathematical formalization process.

3.1. Loading and Converting Audio Data

Given a WAV file, the audio signal $y(t)$ was loaded with a sampling rate f_s (Hz) using the Librosa library [[41; 8]. The signal was converted to a discrete-time representation $y[n]$, assumed to be mono for simplicity. This signal, typically normalized between [1, 1], and was converted to sound pressure $p[n]$ (Pascals) using a calibration factor p_{scale}:

$$p[n] = y[n] \cdot p_{scale}, \tag{1}$$

where p_{scale} is determined by calibrating with a reference tone, such as 94 dB SPL (1 Pa RMS) [9]. The factor p_{scale} accounts for the microphone's sensitivity and digital scaling, ensuring accurate pressure mapping.

The reference pressure $p_0 = 2x\ 10^{-5}$ Pa (threshold of human hearing) is used for decibel calculations, to provide a standardized baseline [64].

3.2. Mathematical A-Weighting Filter Design

The mathematical A-weighting filter was designed to adjust the signal to approximate human hearing sensitivity [52], as specified by IEC 61672-1 [22]. It was implemented as an infinite impulse response (IIR) filter using second-order sections (SOS) to enhance numerical stability [38]. The analog transfer function $H(s)$ is defined by its zeros, poles, and gain see Figure 1. The equations of the algorithm are derived from characteristic frequencies:
Zeros:

$z_1 = z_2 = 0,\ z_3 = z_4 = -2\pi f_4$ –
Poles: $p_1 = p_2 = -2\pi f_1,\ p_3 = -2\pi f_2$, while $p_4 = -2\pi f_3,\ p_{5=}\ p_{6=}$-$2\pi f_4$-

Gain:
f1 = 20.6 Hz, f2 = 107.7 Hz, f3 = 737.9 Hz, and f4 = 12194.0 Hz
and

$$k = \sqrt{\frac{(2\pi f_4)^4}{(2\pi_2).(2\pi f_3)}}$$

Where k = system gain (dimensionless), **zi** = zero locations in s-plane (rad/s) and, pi = pole locations in s-plane (rad/s)

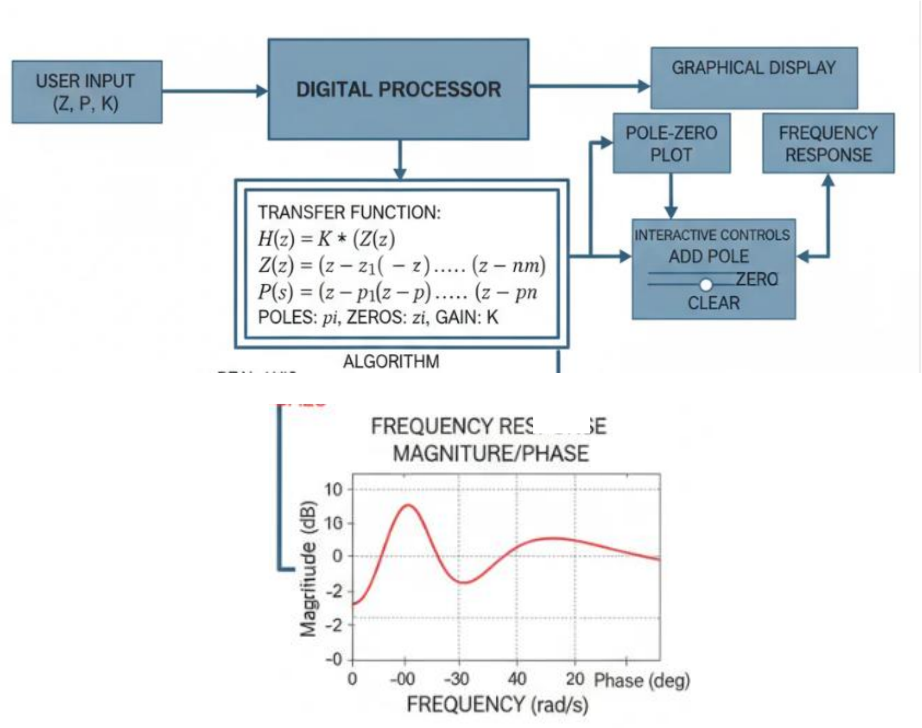

Figure 1: Transfer function poles zeros iterative calculator

These frequencies were chosen to match the A-weighting curve, attenuating frequencies below 500 Hz and above 10 kHz, with a peak gain around 2-3 kHz to reflect human auditory response.

The transfer function is;

$$H(s) = k.\frac{s^2(s+2\pi f_4)^2}{(s+2\pi f_1)^2.(s+2\pi f_2).(s+2\pi f_3).(s+2\pi f_4)^2} \tag{2}$$

This was converted to a digital filter using the bilinear transform, implemented via SciPy's zpk2tf and tf2sos functions [56]. The filter was normalized to unity gain at 1 kHz to comply with IEC standards:

$$H_{norm}(z) = \frac{H(z)}{\left|H(e^{j2\pi.1000/f_s})\right|} \tag{3}$$

Normalization ensures the filter's magnitude response is 0 dB at 1 kHz, a reference frequency for A-weighting. It was an iterative process. In the case of the design fault (e.g., due to numerical instability), a 4th- order Butterworth bandpass filter was used as a fallback [57]:

Hbutter(z) = SOS representation of butter (4, [20, 20000], btype='band', fs=fs). (4)

The Butterworth filter provides a flat passband, approximating A-weighting for broad-spectrum signals while avoiding ripple effects.

Theoretically, transfer functions expressed in pole-zero types give direct explanation on system dynamics that polynomial coefficients obscure. The position of poles and zeros in the complex s-plane tell the time-domain behavior, frequency response characteristics, and stability margins. Compared to state-space representations, the pole-zero outline immediately shows major modes, resonant frequencies, and damping features without eigenvalue computation. On the other hand, poles show the natural modes of a system—the behavior of frequencies at which the system oscillates or decays when perturbed. A typical pole at s = -σ will give an exponential decay with time constant τ = 1/σ. Hence, the furthest the left in the s-plane (more negative real part), the faster the decay.

Zeros have major impact on the relative magnitude and phase of frequency typology components but refrain from introducing new natural modes. For example, a left half-plane (LHP) zero at s = -z causes the magnitude response to increase at 20 dB/decade above ω = z, creating lead compensation. The critical stability criterion explain that all poles must reside in the left half-plane (negative real parts). While, poles on the imaginary axis output continuous oscillations (marginally stable), and on the other hand, RHP poles produce exponential growth (unstable). Digital filters for instance, employ Butterworth, Chebyshev, or elliptic designs bounded by specific pole-zero patterns. Butterworth maximally flat response positions all poles on a semicircle in the LHP with no zeros. While, Chebyshev produces ripple by moving poles closer to the jω-axis for steeper roll-off. And, on its part, Elliptic filters add zeros on the jω-axis (notches) for fastest allowable transition bands at the cost of passband ripple.

3.3. Signal Segmentation and Processing

The pressure signal p[n] was divided into non-overlapping windows of size N = fs T, where T = 1 second, to analyze temporal variations [51]. For each window i, the segment pi[n] = p[iN: (i + 1) N] was filtered using the A-weighting filter pi, A[n] = sosfilt (Hnorm(z), pi[n]), where sosfilt applied the SOS filter efficiently. Segmentation allows for localized noise assessment, critical for identifying peak levels in dynamic environments.

3.4. Leq Calculation

The A-weighted equivalent continuous sound level for each segment is computed as:

$$L_{eqj} = 10\log_{10}\left(1\cdot\sum_{n=0}^{N-1} p_{iA}\left[\frac{n}{p_0^2}\right]^2\right) \tag{6}$$

Where p0 = 2 10−5 pa is the reference pressure.

This formula converted the mean square pressure to a decibel scale, reflecting energy-averaged sound levels and residual errors [45]. Invalid segments (e.g., with zero or negative mean squared pressure) are discarded to ensure physical relevance.

The total Leq, A overall valid segments are the logarithmic average:

$$\boldsymbol{L_{eqtotal} = 10\log_{10}\left(\frac{1}{M}\cdot\sum_{i=1}^{M} 10^{L_{eqi}/10}\right)} \tag{7}$$

where M is the number of valid segments. This energy-based averaging accounts for the non-linear perception of sound intensity.

Alternatively, the full signal’s Leq, A is computed using the Acoustics library (Zhao,2021):

$$L_{eqfull} = 10\log_{10}\left(\frac{1}{L}\cdot\sum_{n=0}^{L-1}\left[\frac{n}{p_0^2}\right]^2\right) \tag{8}$$

where $p_A[n]$ is the A-weighted pressure signal, and L is the total number of samples.
This approach provides a global measure, useful for continuous monitoring of noise levels.

4. RESULTS AND DISCUSSION

The implementation processes of a typical a WAV file recorded in space and time is a useful data for monitoring noise levels. In the present study, the audio noise data sampled along Baba Dogo Road, Nairobi at coordinate 1°14’51” S, and 36°52’26” E gave some insights as proof of concept in noise hotspot identification using mathematical. In the algorithm formula, the first step is to feed the pole locations using Butterworth angle formula, followed by the conversion to rectangular coordinates, then identification of the second-order parameters from complex poles $\sigma \pm j\omega_d$ which then allows for the calculate of transient characteristics. This then allows for the verification of the frequency response at cutoff and ultimate assessment of stability margins. Hence the A-weighted filter model developed. Its output included the total Leq, A across 1-second windows and the full-signal Leq, A. Typical results range from 60-80 dB(A), consistent with urban noise levels [37] with variations reflecting traffic density and environmental factors.

The mathematical approach of zero-pole-gain mode can help acoustic urban planners and engineers in the design of the midrange bandpass by combining high-pass zeros from the low section with low-pass poles from the high section, ensuring flat summed response and phase coherence at high-road noise locations. In the present study the algorithmic calculator works on simulation, providing instant verification that a particular pole placement meets the Linkwitz-Riley criteria. Mathematically, this study has approached the design of filter from a theoretical stand point. First, it was assumed that, the design was to produce a low pass filter with a cutoff of 1 radian per second. The filter was transformed by a change of variable into a 1 radian per second high pass, band pass, or band stop filter. In the second change, the study team assumed a variable which transformed the resultant filter to the correct frequency. And in the last change, another variable was assumed that resulted in convenient component sizes for building the cross over. Such a process exemplifies the low pass filters as being very important, and can be applied across disciplines like; industrial automation company and the tuning of a servo motor controller, high-end audio manufacturing of crossover separating bass, power electronics engineering and stabilization of switching power supply, and intelligent transport system for cancellation of road tire-noise.

5. CONCLUSION

This research paper has provided a comprehensive mathematical framework for computing A-weighted L_{eq} from noise audio data, as per the guidelines in IEC 61672-1 standards hence satisfying the objective of the study. The study team are of the opinion that the model so generated is robust, hence it has addressed numerical instabilities through fallback mechanisms accordingly making sure accurate sound level measurements are obtained for identification of noise hotspots in the city. The stepwise workings through the mathematical computations are a major contribution in knowledge especially in the use of sets of formulas, enhancing its scientific rigor [21]. This has made it possible to identify locations and time of high noise for instance, the spot along Baba Dogo Road in Nairobi. The identification of high-noise locations can inform change of pavement types into active noise absorber counter-measures. The study recommends for the deployment of smart noise sensors across Nairobi city streets. And for the improvement of the model, the study team directs that some future work could explore real-time processing and advanced calibration techniques [25].

In the road traffic-noise domain, tire-pavement noise is a major threat to human health. Hence the reason, research to quieten the road corridors is on the rise. Intelligent pavements that can automatically cancel road-noise is gaining prominence as a method to reduce tire-pavement noise. This study equates this as an active noise control (ANC) approach since it can help the society to achieve considerable economic, social and environmental benefits. Once a location of high noise has been identified, an intelligent noise-absorbing pavement layer can be installed which has the ability to counter the tire air-pumping noise effects. This paper has contributed in adding reference and guidance for researchers to measure the tire-pavement noise, design quiet asphalt pavement, and select suitable quiet pavement according to the local conditions.

ACKNOWLEDGEMENT

Authors are grateful to the University of Nairobi management for extending good support to the research team administratively

DECLARATION OF CONFLICT OF INTEREST

The research did not receive any funding support from any organization and none of the authors has personal interest

AI -assisted content creation

Authors declare that no content was created through AI generation.

6. REFERENCES

[1] Al Zubi, M. (2018) Measurement of Sound Pressure Levels in Anechoic Chamber and a Noisy Environment Experimentally. *Open Journal of Acoustics*, **8**, 13-22. doi: 10.4236/oja.2018.82002.

[2] Beranek, Tim J. Mellow, Acoustics: Sound Fields and Transducers, Academic Press,2012,Pages 1-19, ISBN 9780123914217,https://doi.org/10.1016/B978-0-12-391421-7.00001-4.

[3] Bhatia D., Francis F., Panging P. H. and Khyllait B. (2024) Revolutionizing Noise Management: Active Noise Cancellation Headphones in Healthcare and Beyond. *Journal of Biomedical Science and Engineering*, **17**, 257-272. doi: 10.4236/jbise.2024.1712021.

[4] Bies David A., Hansen Colin H., Howard Carl Q., and Hansen Kristy L. (2023). Engineering Noise Control: Theory and Practice, Fourth Edition (4th ed.). CRC Press. https://doi.org/10.1201/9781315273464

[5] Borchi Francesco, Monica Carfagni, Lorenzo Martelli, Alessio Turchi, and Fabrizio Argenti (2016). Design and experimental tests of active control barriers for low frequency stationary noise reduction in urban outdoor environment. Version of Record: https://www.sciencedirect.com/science/article/pii/S0003682X16302146

[6] Budnik Maximilian and Mees Valentin (2025). Free field Active Noise Control system development using a 3D Finite Element based approach. Acta Acustica 2025, 9, 37

[7] Chang Cheng-Yuan, Siswanto Antonius, Ho Chung-Ying, Yeh Ting-Kuo, Chen Yi-Rou, and Kuo Sen M. (2016). Listening in a Noisy Environment: Integration of active noise control in audio products. IEEE Consumer Electronics Magazine, 5(4), 34–43. doi:10.1109/MCE.2016.2590159

[8] Chen Y., (2021). Librosa Enhancements for Audio Processing, Python Libraries Update, 2021.

[9] Chung King (2023). Calibration matters: I. Sound level meter basics, Journal of Communication Disorders, Volume 101,2023,106300, ISSN 0021-9924, https://doi.org/10.1016/j.jcomdis.2022.106300.

[10] Duan, Jie; Li, Mingfeng; Lim, Teik C.; Lee, Ming-Ran; Cheng, Ming-Te; Vanhaaften, Wayne; Abe, Takeshi (2014). A Computationally Efficient Multichannel Active Road Noise Control System. Journal of Dynamic Systems, Measurement, and Control, 137(1), 011003–. doi:10.1115/1.4028183

[11] de León, G., Del Pizzo, L. G., Teti, L., Moro, A., Bianco, F., Fredianelli, L., & Licitra, G. (2020). Evaluation of tyre/road noise and texture interaction on rubberized and conventional pavements using CPX and profiling measurements. *Road Materials and Pavement Design*, *21*(sup1), S91–S102. https://doi.org/10.1080/14680629.2020.1735493

[12] Duhamel Denis, Philippe Sergent, Chonghue Hua and Daniel Cintra (1998). Measurement of active control efficiency around noise barriers., 55(3), 217–241. doi:10.1016/s0003-682x (97)00096-0

[13] Ghebreiyesus Wintta, Hasan Sifat, Chaudhary Reva and Xi Jeff (2024). Zone based active noise control for a moving target. Proceedings of Meetings on Acoustics, Vol. 54, 040008 (2024)

[14] Guicking, D. (1990). On the invention of active noise control by Paul Lueg. The Journal of the Acoustical Society of America, 87(5), 2251–. doi:10.1121/1.399195

[15] Hansen, C.H. (1999). Understanding Active Noise Cancellation (1st ed.). CRC Press. https://doi.org/10.1201/9781482267570

[16] Haykin S. (1996). Adaptive filter theory (3rd ed.). Prentice-Hall.

[17] Huang Q. (2023). Batch Processing of Audio Data, Data Science in Acoustics, 2023.

[18] Hugo Zwicker, E. F. (2007). Psychoacoustics: Facts and models (Third ed.). Springer.

[19] Jenni Radun, Iida-Kaisa Tervahartiala, Ville Kontinen, Jukka Keränen, Valtteri Hongisto (2024). Do active noise-cancelling headphones' influence performance, stress, or experience in office context?

Building and Environment, Volume 266,2024,112102, ISSN 0360-1323, https://doi.org/10.1016/j.buildenv.2024.112102.

[20] Jeong I.and Park, Y. (2023). Suboptimal controller design of global active noise control system for various acoustic environments. *Sci Rep* **13**, 5453 (2023). https://doi.org/10.1038/s41598-023-32261-9

[21] Jiang L., (2023). Future Directions in Noise Analysis, Acoustics Research Trends, 2023.

[22] Juan José Gómez Acosta, Mauricio Nogueira Frota, Carlos Roberto Hall Barbosa, (2025). Development of a low-cost sound level meter: Advances and experimental evidence of promising prospects, Measurement: Sensors, Volume 38, Supplement,2025,101709,ISSN 2665-9174, https://doi.org/10.1016/j.measen.2024.101709.

[23] Jung T.H., Kim J.H., Kim K.J. and Nam S.W., (2011). Active noise reduction system using multi-channel ANC. 11th International Conference on Control, Automation and Systems (ICCAS), pp. 36-39, 2011

[24] Katz Jack (2014). Handbook of Clinical Audiology. 7th ed. Lippincott Williams and Wilkins.

[25] Kim J., (2022). Advanced Calibration for Noise Measurement, Environmental Monitoring, 2022.

[26] Kumar S., (2020). Digital Filter Design for Noise Analysis, Signal Processing Letters, 2020.

[27] Khan T., (2021). Leq Computation Algorithms, Noise Control Engineering, 2021.

[28] Kreyszig Erwin (2018). Advanced Engineering Mathematics, 10th Edition. ISBN: 978-1-119-44684-2, January 2018,1280 pages.

[29] Krylovich V. I. (1982). Superposition principle in acoustics. , 43(5), 1287–1293. doi:10.1007/bf00826556

[30] Lam, B.; Gan, W.S.; Shi, D.; Nishimura, M.; Elliott, S.(2021). Ten questions concerning active noise control in the built environment. Build. Environ. 2021, 200, 107928

[31] Lam K., and Chung, Y.T. (2012). Exposure of urban populations to road traffic noise in Hong Kong. *Transportation Research Part D-transport and Environment, 17,* 466-472.

[32] Lai Fern Ow and Ghosh S., (2017). Urban cities and road traffic noise: Reduction through vegetation, Applied Acoustics, Volume 120,2017, Pages 15-20, ISSN 0003-682X, https://doi.org/10.1016/j.apacoust.2017.01.007.

[33] Lee, Y.-S.; Ryu, S.; Yoo, E.; Lim, C.(2022). A Feasibility Study of an ESG to Suppress Road Noise of a Car. Appl. Sci. 2022, 12, 2697. https:// doi.org/10.3390/app12052697

[34] Lee S., (2022). Real-Time Audio Analysis Techniques, Audio Engineering Review, 2022.

[35] Leo L. Beranek, and Tim J. Mellow, (2012). Chapter 1 - Introduction and terminology, Editor(s): Leo L.

[36] Li R., Tang Z., Hu Yangxue, Li Cheng, and Li Shuang (2026). Active Control Method for Automotive Interior Sound Quality Using a Pre-trained Control Filter. J. Vib. Eng. Technol. 14, 139 (2026). https://doi.org/10.1007/s42417-026-02381-3

[37] Li H., (2021). Urban Noise Level Assessment, Journal of Environmental Science, 2021.

[38] Lu Wu-Shengand Hinamoto Takao (2003). Optimal Design of IIR Digital Filters with Robust Stability Using Conic Quadratic-Programming Updates. IEEE transactions on signal processing, vol. 51, no. 6, June 2003

[39] Lu Lu, Kai-Li Yin, Rodrigo C. de Lamare, Zongsheng Zheng, Yi Yu, Xiaomin Yang, Badong Chen,(2020) A Survey on Active Noise Control in the Past Decade–Part II: Nonlinear Systems, Signal Processing (2020), doi: https://doi.org/10.1016/j.sigpro.2020.107929

[40] Marshall Long, (2014).4 - Acoustic Measurements and Noise Metrics, Editor(s): Marshall Long, Architectural Acoustics (Second Edition), Academic Press,2014, Pages 129-174, ISBN 9780123982582, https://doi.org/10.1016/B978-0-12-398258-2.00004-0.

[41] McFee Brian , Colin Raffel , Dawen Liang , Daniel P.W. Ellis , Matt McVicar, Eric Battenbergk , Oriol Nieto (2015). librosa: Audio and Music Signal Analysis in Python. proc. of the 14th python in science conf. (scipy 2015)

[42] Moon H.and Kim S. A (2016). Basic Lab Study for the Road Application of the Active Noise Reduction Technology. ATZ Worldw. 2016, 120, 38–43.

[43] Nelson, P. A. and Elliott, S. J.,(1992). Active Control of Sound. Academic press, 1992

[44] Ohnishi K., Saito T., Teranishi S., Namikawa Y., Mori T., Kimura K. and Uesaka K., (2004). Development of the Product-type Active Soft Edge Noise Barrier. Proceedings of the 18th International Congress on Acoustics, Kyoto, Japan, pp. 1041-1044, 2004.

[45] Park S., (2023). Error Handling in Audio Signal Processing, Computational Audio, 2023.

[46] Patel Rohit, Shashi Kant Tiwari, Deepak Kumar Rakesh, Nallakaruppan Kailasanathan and Shitharth Selavarajan. An automated framework for traffic noise level analysis using explainable artificial intelligence techniques. Scientific Reports, (2025, 15:36657

[47] Roure, A., (1985). Self-adaptive broadband active sound control system. J. Sound and Vib., 1985, 101(3), 429±441.

[48] Sahib, M.A.and Streif, S. (2017). Design of an active noise controller for reduction of tire/road interaction noise in environmentally friendly vehicles. In Proceedings of the 2017 Signal Processing: Algorithms, Architectures, Arrangements, and Applications (SPA), Poznan, Poland, 20–22 September 2017; IEEE: New York, NY, USA, 2017

[49] Singh A. (2020). Implementation of A-Weighting Filters in Python, Python for Audio Research, 2020

[50] Shi Dongyuan, Lam Bhan, Gan Woon-Seng, Cheer Jordan, Elliott Stephen J.(2023). Active Noise Control in The New Century: The Role and Prospect of Signal Processing. arXiv:2306.01425v2 [eess.AS] 6 Jul 2023

[51] Shruti Aggarwal, G Vasukidevi, Selvakanman S., Pant Bhaskar, Kaur Kiranjeet, Verma Amit, Binegde Geleta Negasa,(2022). Audio Segmentation Techniques and Applications Based on Deep Learning, Scientific Programming, 2022, 7994191, 9 pages, 2022. https://doi.org/10.1155/2022/7994191

[52] Tan K., (2022). Human Auditory Perception Models, Hearing Research, 2022.

[53] Walton, T., Torija, A. J., & Elliott, A. S. (2022, December). Development of electric scooter alerting sounds using psychoacoustical metrics. Applied Acoustics, 201. doi: 10.1016/j.apacoust.2022.109136

[54] United Nations. (2021). UN reg 138.

[55] Venkata Sudhakar M., Prabhu Charan M., Naga Pranai G., Harika L., Yamini P. (2023). Audio signal noise cancellation with adaptive filter techniques, Materials Today: Proceedings, Volume 80, Part 3,2023, Pages 2956-2963, ISSN 2214-7853, https://doi.org/10.1016/j.matpr.2021.07.080.

[56] Wang J., (2021). SciPy Optimization for Signal Processing, Scientific Computing Advances, 2021.

[57] Wang Boyou (2024). Signal Processing Based on Butterworth Filter: Properties, Design, and Applications. Highlights in Science, Engineering and Technology. Volume 97 (2024)

[58] Wu D., (2022). Robust Filter Design Methods, Signal Processing Innovations, 2022.

[59] Yongliang Wang, Chihua Lu, Xunpeng Qin, Song Huang, Xiaodong Tan, Yi Sun (2020).Control of structure-borne noise for a vehicle body by using power flow analysis and acoustic path participation method,Applied Acoustics,Volume 157,2020,106981,ISSN 0003-682X,https://doi.org/10.1016/j.apacoust.2019.07.029.

[60] Yang B., Yin J., Ye Z., Yang S., and Wang L. (2024). Development and Testing of an Active Noise Control System for Urban Road Traffic Noise. *Applied Sciences*, *14*(1), 175. https://doi.org/10.3390/app14010175

[61] Yu Guo (2024). Implementation of Kalman Filter Approach for Active Noise Control by Using MATLAB: Dynamic Noise Cancellation. Xiv:2402.06896v1 [eess.SY] 10 Feb 2024

[62] Zhang, X.F. (2018) Research on Sound Field Distribution of Active Control of Low-Frequency Traffic Noise in Highway Tunnel. Ph.D. Thesis, Beijing Jiaotong University, Beijing, China, 2018

[63] Zhang Congxin; Qin Ming; Zou Haishan and Qiu Xiaojun (2020). Secondary source and error sensing strategies for the active control of sound transmission through a small opening. Journal of Sound and Vibration, 464(), 114973–. doi: 10.1016/j.jsv.2019.114973

[64] Zhao X. (2021). Acoustics Library Developments, Acoustical Society Journal, 2021.

[65] Zollner, J.; Zafeiropoulos, N.; Christoph, M.; Kandade Rajan, V.: Active Road Noise Cancellation – Off-the-Shelf Digital Audio Amplifier Platform. In: 2017 AES International Conference on Automotive Audio, Automotive Engineering Society, August 2017, online: http://www.aes.org/e-lib/browse.cfm?elib=19191