A NEW ACTIVE CONTROL APPLICATION FOR REDUCTION OF ENVIRONMENTAL NOISE IN OPEN SPACES

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ABSTRACT

A NEW ACTIVE CONTROL APPLICATION FOR REDUCTION OF ENVIRONMENTAL NOISE IN OPEN SPACES

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Today, rapid development of urban and industrial areas, growing motorway, airway and railway networks together with other sources, bring out noise as one of the major environmental problems. Studies show that one of the most annoying noise sources is the traffic noise in the cities. Sound barriers are conventional solutions applied to control traffic noise. However, the construction cost of these barriers, their aesthetical qualities and how they contribute to urban qualities are questionable. Today's modern tools offering higher computation power, greater ability of collecting precise data for real time audio processing, drastically increased the application possibilities of Active Noise Control (ANC) in different scales including but not limited to personal protection, HVAC systems, automotive and aerial vehicle cabins, medical imaging and lastly in urban scale. In this thesis, ANC is proposed as a method to be applied to open spaces or as an alternative, a performance increasing add on to sound barriers to control the environmental noise and decrease its negative effects on human health.

Keywords: Active Noise Control, Environmental Noise, Digital Signal Processing

ÖZ

AÇIK ALANLARDAKİ ÇEVRESEL GÜRÜLTÜNÜN AZALTIMI İÇİN YENİ BİR AKTİF KONTROL UYGULAMASI

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Günümüzde, diğer kaynaklarla beraber kentsel ve endüstriyel alanların hızlı gelişimi, kara, hava ve tren ağlarının büyümesi, gürültünün başlıca çevresel problemlerden biri haline gelmesine sebep olmuştur. Araştırmalar, trafik gürültüsünün şehirlerdeki en rahatsız edici gürültü kaynaklarından biri olduğunu ortaya koymuştur. Ses perdeleri trafik gürültüsünün kontrolü için konvansiyonel çözümlerdir. Ancak, bu perdelerin inşa maliyetleri, estetik nitelikleri ve kente nasıl katkılarının bulunduğu tartışmalıdır. Günümüzün modern araçlarının daha fazla hesaplama gücü, gerçek zamanlı ses işleme için daha yüksek kesinlikte veri toplama kabiliyeti Aktif Gürültü Kontrolü (AGK-ANC)'nün farklı ölçeklerde uygulama olasılığını önemli bir şekilde arttırmıştır. Kişisel korunma, HVAC sistemleri, otomobil ve hava araçları kabinleri, tıbbi görüntüleme ve şehir ölçeği bu uygulamalara örnek olup bu örneklerle sınırlı değildir. Bu tezde, çevresel gürültünün kontrolü ve insan sağlığı üzerinde olumsuz etkilerinin azaltımı için açık hacimlerde uygulanması amacıyla ya da ses duvarlarına bir alternatif olarak, performansını arttırıcı eklenti olarak AGK; bir yöntem olarak önerilmiştir.

Anahtar Kelimeler: Aktif Gürültü Kontrolü, Çevresel Gürültü, Sayısal Sinyal İşleme

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$a(n)$	Coefficient vector of adaptive filter.
$A(z)$	Transfer function of adaptive filter.
$C(z)$	Transfer function of the adaptive controller.
$d(n)$	Noise signal to be cancelled.
$D(z)$	z-transform of the noise signal to be cancelled.
$e(n)$	Error signal, residual error.
$E(z)$	z-transform of the error signal.
f_c	Center frequency of a 1/3 octave band
f_c^{high}	Highest frequency of a 1/3 octave band
f_c^{low}	Lowest frequency of a 1/3 octave band
$H(z)$	Transfer function of feedback ANC.
L	Length of the filter.
L_{eq}	Equivalent continuous sound pressure level (dB).
L_{max}	Maximum RMS sound pressure level during a measurement period or a noise event.
L_{min}	Minimum RMS sound pressure level during a measurement period or a noise event.
Ln	Noise level exceeded for n% of the measurement time.
L_p	Sound pressure level.

L_{peak}	Peak value of the sound pressure level within the measuring period.
N	Time index.
$P(z)$	Transfer function of the primary path: acoustic path from reference microphone to error microphone.
P_l	Sound pressure in Pa.
P_r	Reference sound pressure in Pa.
$S(z)$	Transfer function of the secondary path, electro-acoustic path from the output of the controller to the output of the error microphone.
$\hat{S}(z)$	z-transform of the secondary path estimate.
T_{sweep}	Length of the sweep signal in seconds.
$x(n)$	Noise signal to be cancelled, captured by reference microphone.
$X(z)$	z-transform of the noise signal to be cancelled.
$y(n)$	Control signal.
$Y(z)$	z-transform of the control signal.
μ	Learning rate of the adaptive filter.
$\xi(n)$	Cost function.

CHAPTER 1

INTRODUCTION

1.1. GENERAL

Starting from the industrial revolution, technological developments not only came into human life with all of the comfort factors they bring together, but also created new problem domains to be solved in micro and macro scale. Rapid urbanization, industrialization and continuously increasing population force the limits of environment. Especially in cities, these problems are threatening the well-being of citizens who are exposed to severe pollutions.

Environmental noise, which is accepted as the third largest environmental pollution type according to World Health Organization (World Health Organization, 2011) with its measurable and unmeasurable, direct and indirect side effects on individuals and communities, resulting in severe health problems in mid and long term as well as loss of workforce.

It is known that the most important source of noise in urban areas is traffic noise. Annoyance caused by traffic noise is becoming more and more problematic with the rapidly growing transportation networks and drastically increasing traffic capacity. The number of citizens effected by the traffic noise in Europe today is reached to 125 millions (European Environment Agency, 2014). Therefore, traffic noise is a subject matter for urban planning and noise control action.

Governments and non-governmental organizations already started to work on the problem by identifying the reasons, short and long term effects. Moreover, for the preparation of strategic action plans, preparation of noise maps is already became obligatory.

Starting from 2002, most of the European Union countries and Turkey in 2010, published directives covering the evaluation and control of environmental noise including maximum allowable environmental noise levels as well as enforcement of action plans in order to decrease the noise levels caused by urban and suburban traffic, at dwellings (residences) and critical areas that can be exemplified as hospitals, houses of worship, and educational establishments (Commission of European Communities, 2002) (Çevresel Gürültünün Değerlendirilmesi ve Yönetimi Yönetmeliği, 2010).

Regulations in force and standards clearly states the limiting values and obligates the stakeholders in taking the required precautions. However, methods of controlling the environmental noise are limited. Most of the control applications are economically infeasible and requires site specific design considerations both in building and urban scale.

One of the most common approach is to use passive noise barriers, which are used as a mean of controlling the noise in the close vicinity of the noise sources like industrial sites, motorways and railways. In order to achieve noise criterion targeted in the regulations, application of passive noise barriers in the critical areas, which are especially around main roads, is inevitable. Performance and efficiency of the passive barriers to be designed and applied highly depend on the height and the form of the barrier, construction material selected, level of the noise and frequency spectrum of the noise source to be considered. Performance of passive barriers decreases in time by changing noise characteristics on daily or long-term basis. Moreover, designed noise barriers may not fit in the urban texture and cause visual pollution. Also, the manufacturing costs of the noise barriers are high and implementation to the site is difficult and costly. Hence, it is quite common to see that, even noise barriers are necessary for a specific noise source, due to the drawbacks presented above, they are not implemented in most cases.

There are quite few examples of the noise barriers contributes to the urban qualities since their scale is determined by the level of noise and noise reduction performance based material selection, without regarding the spatial qualities. Example of some conventional passive noise barriers are presented in Figure 1.

Figure 1: Generic noise barrier applications.

In this thesis, as an alternative to passive noise barriers which are disadvantageous because of variety of reasons, ANC, an electro-acoustic mean of reducing noise, is proposed for the controlling of traffic related environmental noise.

ANC, which can be defined as reduction of noise (sound) using another sound source, is not a new concept in engineering literature. Yet, today's advanced digital design tools offering high computation power, electro-acoustic sensors (microphones) with greater ability of collecting precise data and digital signal processors which are more eligible for real time audio processing, drastically increased the application possibilities of ANC in different scales.

Implementation possibilities of ANC can be seen in many different areas from personal product level to industrial and commercial applications.

Some groundbreaking implementations include but not limited to personal noise cancelling headphones, HVAC noise cancelling systems, household equipment, noise reduction systems embedded to automobile and aerial vehicle cabins and as it is proposed in this thesis, as a part of environmental structures.

The number of applications and diversity are increasing continuously in parallel with the advances in digital signal processing (DSP) methods and DSP hardware, making ANC more prominent than ever in noise control today.

1.2. OBJECTIVE AND SCOPE OF THE THESIS

In this thesis, *'Active Noise Barrier'* is proposed as a standalone system, which can be installed for noise reduction at open spaces where high noise is present and the use of sound barriers is not possible or adequate. The proposed active noise barriers can be used on sites where the noise exposure limits are exceeded. Unlike conventional passive noise barriers, working with the principle of controlling the noise on the source, proposed system brings the idea of controlling the noise at receiver point or in the neighborhood. Hence, the required space is also decreased compared with bulky passive sound barriers. This study has pioneering characteristic by means of application of active noise control at outdoor spaces and areas as well as in urban scale.

The research conducted in cooperation with a product development project sponsored by Republic of Turkey, Ministry of Science, Industry and Technology SANTEZ R&D incentive. It is aimed to provide a prototype to be implemented for controlling the environmental noise. The ANC algorithm and the prototype are tested by using the noise data collected in different areas.

In the scope of the thesis, as a step-by-step methodology, firstly in order to be able to understand the characteristics of the traffic noise, on site noise measurements were conducted. According to the characteristics of the noise, applicable control strategy and algorithm were selected. Then, system architecture was decided in accordance with the applied control strategy. After the implementation of the algorithm to the controller hardware, test and validation measurements were conducted. During the validation studies, noise profiles obtained from the field measurements were employed in order to model the characteristics of traffic noise.

The study shows that, ANC applications are suitable for outdoor environmental noise control in terms of performance, ease of application and hardware cost. Moreover, scalable size and effect of the system make it applicable to special, attention and detailing required architectural solutions.

1.3. DISPOSITION

This thesis aims to argue the proposed product/method in six chapters.

In Chapter 2 Information on environmental noise and related regulations arepresented in order to underline the importance of the issue. Moreover, a detailed literature survey on ANC is conducted in order to express the potentials of the method and indicate the direct relation between applicability and hardware.

Chapter 3 gives brief information about the environmental noise and parameters used to evaluate the environmental noise. Also in this chapter, active noise control theory, as well as adaptive filter algorithms, which are the backbones of contemporary applications are presented. The most common ANC approaches are compared regarding the available instrumentation and noise characteristics. Appropriate system architecture and control action match is proposed.

Chapter 4 starts with presenting and analyzing the data collected with the on-site noise measurements conducted in order to understand the characteristics of the noise sources concerned. Gathered data is analyzed in order to specify the system requirements and design the case studies. Also, this chapter describes the components of the proposed system, validation test setup and measurement conditions

Chapter 5 focuses on the results of the tests and measurements conducted to determine the performance of the proposed system. Discussions on the comparison of the results from different cases are made.

Finally, in Chapter 6, thesis is concluded with the discussions on outcomes of the study, brief argument of possible applications of system to outdoor living areas and possible future work recommendations.

CHAPTER 2

LITERATURE AND STATE-OF-ART

2.1. ENVIRONMENTAL NOISE, REGULATIONS, ACTIONS

Environmental noise pollution is a term to describe the sounds caused by traffic, industry, construction and other sources, which adversely affect living comfort of community. Noise, which directly or indirectly causes variety of different health problems, is accepted as one of the main source of environmental pollution.

Studies conducted in recent years show that, more than 30% of the EU population encountered medical problems related to noise (Houthuijs, van Beek, Svaart, & van Kempen, 2014). A more detailed report published by European Environmental Agency defines noise pollution as a major environmental health problem in Europe, which causes 10.000 cases of premature death, 900.000 cases of hypertension and 43.000 hospital admissions each year. Moreover, 20 million adults are affected by noise-induced annoyance while 8 million adults suffer sleep disturbances due to environmental noise. It is estimated that; 125 million people are affected from road traffic noise, which is the most dominant noise source (European Environment Agency, 2014).

Emerging as the most important issue right after the air quality, unless no precautions taken, noise seems to become a more severe problem in the very short term.

As an environmental problem, noise has been an important concern for national and international authorities both in administrative and academic context. This rapidly spreading problem forces governments to take new measures and requires developing new strategies to tackle with. One of the very first acts against noise problem by developing a coordinated policy titled as Towards Sustainability dates back to 1993

(Commission of the European Comminities, 1993). Outcomes of the study were resulted in a series of actions enforced by European Parliament (Commission of the European Communities, 1998).

Also in 1996, European Commission published Green Paper on Future Noise Policy (Commission of the European Communities, 1996) which identifies three key areas for dealing with noise as; elimination of knowledge gap between member states, involvement of public, necessity of an integrated strategy towards a better quality of life.

A more in depth action by European Commission was taken with the release of EU directive 2002/49/EC (Commission of European Communities, 2002). The Environmental Noise Directive (END) can be considered as the major step towards to develop a common approach to control environmental noise in EU. END aims to prevent/reduce the harmful effects like health effects, speech interference, annoyance created by major noise sources like road, railway, airport traffics, industry, noise emitted by recreational facilities. It also aims to harmonize noise indicators and assessments, providing a common ground to compare noise levels in different member countries, and create a public awareness of noise and its effects as an environmental problem. One of the main instruments of END in achieving noise control is the preparation of strategic noise maps, which are obtained by common assessment methods, accepted in EU, showing exposed noise levels. END requires that all the information obtained on noise pollution should be publicly available prior to take further actions in planning.

Within the frame of Turkey's European Union integration, regulations regarding the evaluation and control of environmental noise (Çevresel Gürültünün Değerlendirilmesi ve Yönetimi Yönetmeliği, 2010) is accepted and published by Ministry of Environment and Forestry in accordance with END (2002/49/EC). Precautions featured in the regulations include the maximum allowable environmental noise and necessary actions to be taken in order to decrease the noise caused by urban and suburban traffic, at dwellings (residences) and critical areas that can be exemplified as hospitals, houses of worship, and educational establishments.

Moreover, with this regulations, for the urban areas having population more than a declared threshold, preparation of noise maps is obligatory and prepared maps should be updated in each five-year period.

As the reports, directives and regulations implies, environmental noise is accepted as a major problem by governments, administrative authorities and civil society. Although administrators try to induce new regulations in order to decrease the number of effected citizens, there is no regulation and a proposed method regarding the on-point control applications.

Noise as an environmental issue, is in the agenda of public authorities, in order to decrease its negative effects on public health and economy. In future, even stricter regulations may be accepted, outdating the present control strategies. Hence, by the time, reductions obtained with conventional passive noise barriers may not be sufficient and new approaches should be developed.

Introduction of active noise control to the environmental noise problem has potential to lead new ways for unblocking the potential, future bottlenecks.

2.2. ACTIVE NOISE CONTROL

Studies related to ANC transformed from a theoretical frame to a fruitful and promising research work with the newly emerging electronics and computer technologies at the last quarter of the 20th century, leading in pioneering application examples. On the other hand, although the theory is very promising, studies on the implementation slowed down for a while, due to practical problems related with the hardware used, limitations on computational capacities of the computers, lack of detailing in the used mathematical models in definition of such complex and multi-dimensional and broadband sound fields. Starting from 2008, studies on ANC regained speed, new application areas were emerged and used systems started to become more efficient.

Recent studies on the field can be classified into two main groups: focusing on the development and enrichment of the filtering algorithms used with more complex approaches and development of the algorithms for the nonlinearities present in the noise source, control systems and elector-acoustic components. Starting from 2010, ANC studies are more focused on the implementation and on new possible application areas as alternative to conventional applications. Studies classified into this group can be referred as the driving force for the research and development of the hardware, which is crucial for ANC. In the following part, some benchmark studies on ANC are presented.

One of the important studies is conducted in 1991. Ahuja and Stevens compiled the studies done on the ANC and summarized the basic applications made until 1990s. Air ducts, aircraft cabins, noise caused by the transformer and fans are defined as the primary application areas (Stevens & Ahuja, 1991). Basic implementation strategies about ANC outlined in the same article. Moreover, basic concepts namely, single source, multiple sources, free-field, near field, narrow band and broadband are defined as well as the filters and algorithms used in the control functions are outlined. The same article also identified possible future research areas and especially underlined the importance of frequency selective applications. Today, control functions, hardware and software used for ANC went far beyond the level predicted for that day. Also, applications are diversifying with every single study. Advances in processor technology have provided the appropriate computing environment for development and application of non-linear and adaptive filters, which require high computing power to the proposed systems.

Work published by Tan and Jiang in 1997 indicates that nonlinearities in ANC systems can effectively be modeled using Truncated Volterra Series. A series of second order filtered-x adaptive algorithms were developed in the scope of the same study. Algorithm that updates the filter weights were named as VFxLMS – Volterra filtered x-LMS (Tan & Jiang, 1997). Although proposed method was successful for modelling the nonlinearities, algorithms developed were computationally costly for the implementation.

In 2004, Das and Panda proposed a new ANC system structure based on a new FSLMS algorithm. The studied algorithm was derived using FLANN (functional link artificial neural network) structure. Computer simulations carried out under the scope of the aforementioned study showed that the proposed system is more successful than standard FxLMS and VFxLMS algorithms. Also, in certain cases, the proposed FSLMS based algorithm has shown superiority over VFXLMS in terms of calculation time (Das & Panda, 2004). This study shows that better performing algorithms does not necessarily require higher computational cost.

In 2004, Zhang and Woo-SengGan, suggested the use of simplified fuzzy neural network approach for ANC systems. Due to its low computational power and less complicated hardware requirements, FXLMS (filtered-x least mean square) algorithm was utilized for the calculation of finite impulse response filter of proposed adaptive ANC system. In the scope of the study, different adaptive algorithms are employed to increase the performance and reduce the computational sources required.

With the more advanced digital hardware and signal processors, more complicated algorithms were developed for the cases where phase difference is unbalanced and non-stationary, as well as where the system and signals are non-linear.

In their study, Zhang and Woon-Seng Gan, developed an artificial neural network based control function and applied the control strategy to increase the learning rate thus, decreasing the settling time of the filter (Zhang & Gan, 2004).

In 2005, Kuo and Wu proposed a bilinear FXLMS algorithm for non-linear adaptive filters as a solution to nonlinearities, especially emerged by saturation of the dynamic range of the electronic systems by generated noise control signals, as well as other nonlinearities in real, linear ANC applications (Kuo & Wu, 2005). Study highlights the application possibilities of ANC to real and wide range of applications.

Tarabini and Roure conducted a research on variables that effect the performance of ANC systems in a closed volume. They aimed decreasing the sound transmission properties of a sound-insulating wall, with the help of a ANC application with the computational model they developed. The room is modeled with the image source method as a rectangular enclosure with a stationary point source; the active barrier is set up by an array of loudspeakers and error microphones and is meant to minimize the squared sound pressure on a wall with the use of a decentralized control. Influencing parameters and their effects on the system performances are identified with a statistical inference procedure. In the investigated configuration performances are analyzed in a frequency range of 25 hz - 300 hz at discrete 25 hz steps. The surface attenuation and the diagonal control stability are mainly driven by the distance between the loudspeakers and the error microphones and by the loudspeakers directivity; minor effects are due to the distance between the error microphones and the wall, by the wall reflectivity and by the active barrier grid meshing. Room dimensions and source position have negligible effects (Tarabini & Roure, Modeling of influencing parameters in active noise control on an enclosure wall, 2008). Study was pioneering as the developed system employs a model of the room for calculation of the control signals.

Akhtar, Abe and Kawamata proposed a simultaneous online acoustic feedback path modeling method for the cases where powerful acoustic feedback is present. Proposed approach ensures the stability of the used adaptive filters and decreases the convergence time even for the ANC systems with time varying acoustic feedback paths. They integrated three different filters in order for proposed ANC system to work with narrow-band, broadband, random or periodic noise signals (Akhtar, Abe, & Kawamata, 2007). Method proposed with the conducted study was an important step for real time modelling of the time varying behavior of acoustic paths, eliminating the acoustic feedback problem in ANC systems designed with feedback strategy.

Chen and Too explored the effects of sound elimination in a cylindrical duct by combining a reactive muffler and ANC system. (Chen & Too, 2009). Hybrid control system composed of diverse control actions are shown to be successful. Another important result of the study, besides the exploration via experiment of the combined noise control system, a Grey prediction based on Grey Theory is also applicable to ANC.

Starting from 2010, researchers focused more on possible implementation of ANC for end users. Subject of the studies targeted walls, windows and noisy machines.

As an example, Tarabini, Roure and Pinhede describes a local active noise control system that virtually increases the sound isolation of a dividing wall by means of a secondary source array.

Proposed method is based on reduction of sound pressure on the source side of a partition using an array of loudspeakers that generates destructive interference on the wall surface, where an array of error microphones is placed. In order to decrease the large number of actuators required for the task, FxLMS algorithm is utilized. With the use of different microphone-speaker configurations, they achieved 10dB reduction between 50 - 300 Hz frequency bands (Tarabini, Roure, & Pinhede, Active control of noise on the source side of a partition to increase its sound isolation, 2009).

Li and Cheng studied on the design and experimental validation of the structural acoustic sensors to be used for the noise reduction in irregular enclosed volumes with ANC. Study shows that, with the synthesized structural acoustic sensors, necessity of using microphones for the sensing of error signals of an ANC system can be eliminated. Both SISO (single input and single output) and MIMO (multi-input and multi-output) control systems are optimally designed using Genetic Algorithms and implemented with a Filtered-X Feedforward LMS controller in the scope of the study (Li & Cheng, 2010).

In 2010, Chen, Pu and Qiu proposed a new compound secondary source, based on the analysis of active noise control system with multi-channel monopole secondary sources. As a result of their study they show that, the proposed compound secondary sources control system can provide higher noise reduction for free field noise radiation control with the same number of control channels (Chen, Hongjie, & Xiaojun, 2010).

Researchers working on real use cases encountered new and application specific problems. However, presence of the problems enforced researchers to come up with new ideas, which solved these problems and even can be employed in areas other than ANC.

ANC system proposed by Hu, Yu and Rajamani for a home window, using a transparent acoustic transducer is an important example. In their case, error and reference microphones would pick up both external and internal sound. This leads to adverse effects on the performance of the active noise cancellation system and also to distortion of the internal sound. In order to overcome this problem, a wave separation technique is proposed to separate the internal and external components of sound. The performance of the resulting ANC system show that the new system is able to accurately preserve desired internal sound while cancelling uncorrelated external noise (Hu, Rajamani, & Yu, 2013). Moreover, this study shows that for specific applications, use of new materials are required.

As another real time application example in 2011, Ardekani and Abdulla conducted a new convergence analysis for filtered-x LMS-based active noise control systems with band-limited white noise and moving average secondary paths. Based on the linear model developed for the adaptation process, the upper bound of the adaptation step-size is derived. Also, the adaptation step-size leading to the fastest convergence rate is derived (Ardekani & Abdulla, 2011).

George and Panda proposed a novel filtered-su LMS (FsuLMS) algorithm based ANC system, which employs a convex combination of an adaptive IIR filter with a functional link artificial neural network (FLANN), with an objective to improve the performance. Simulation study conducted in the scope of the work reveals enhanced performance of the proposed system over that of its component filters (George & Panda, On the development of adaptive hybrid active noise control system for effective mitigation of nonlinear noise, 2012). In their following study, again they proposed a novel nonlinear ANC system based on a cascade of a FLANN filter and a Legendre polynomial. The performance of the new controller has been compared with that obtained by a FLANN based ANC system trained using a filtered-s least mean square (FsLMS) algorithm as well as with a Legendre neural network (LeNN) based ANC system trained using a filtered-l LMS (FlLMS) algorithm. The training of the cascaded controller has been achieved using a filtered-sl LMS (FslLMS) algorithm, which simultaneously adapts the weights of both the component adaptive controllers. Simulation study reveals improved performance over FLANN based ANC systems (George & Panda, Active control of nonlinear noise processes using cascaded adaptive nonlinear filter, 2013).

Another important work published in 2013 by Hu, Rajamani and Yu, proposes the idea of using a transparent thin film speaker in a home window to provide both an invisible audio playback device and an active noise cancellation system. As, a traditional feed-forward active noise cancellation system uses direct microphone measurements for both reference and error signals, both the audio playback and the noise cancellation performance can degrade. Hence, in the scope of the work, in addition to a wave separation algorithm, an online adaptive secondary transfer function estimation method is used for accurate removal of the audio component from the error signal. Experimental results show that the developed system can preserve the auxiliary audio sound while cancelling external noise effectively (Hu, Rajamani, & Yu, 2012).

As a real implementation study, Yang et al. implemented ANC to a high-speed elevator, in order to reduce motor and rope noise transferred to cabin (Yang, Jeong, Jeong, Kim, & Oh, 2014). Using moving band pass filters and correlation filtered X-LMS algorithms, they achieved a reduction up to 8 dB at ear level.

In 2016, Ryu and Lee examined the effect of distance between ear and the error microphone embedded to the proposed active headrest system which works with a virtual-microphone based FXLMS algorithm. Using the variations between ear and the error microphone, system was able to reduce a narrowband noise up to 22 dB. Study reflects that for effective application of the approach to the real case, estimations to model the acoustic paths should be precisely made. Moreover, use of multiple channel systems are offered as a step to real product design (Ryu & Lee, 2016).

Detailed analysis on current literature shows that advances in active noise cancellation theory and technological developments on related processing, sensing and driving hardware are progressing very rapidly, especially in the last decades. Benchmark studies on ANC are summarized in Figure 2.

As can be seen in Figure 2, starting from 2010 the diversity of the ANC applications are increasing more and became more prominent owing to the developments on both hardware and software.

This thesis will contribute to the literature by focusing on application of ANC to environmental noise, which is rarely seen in literature.

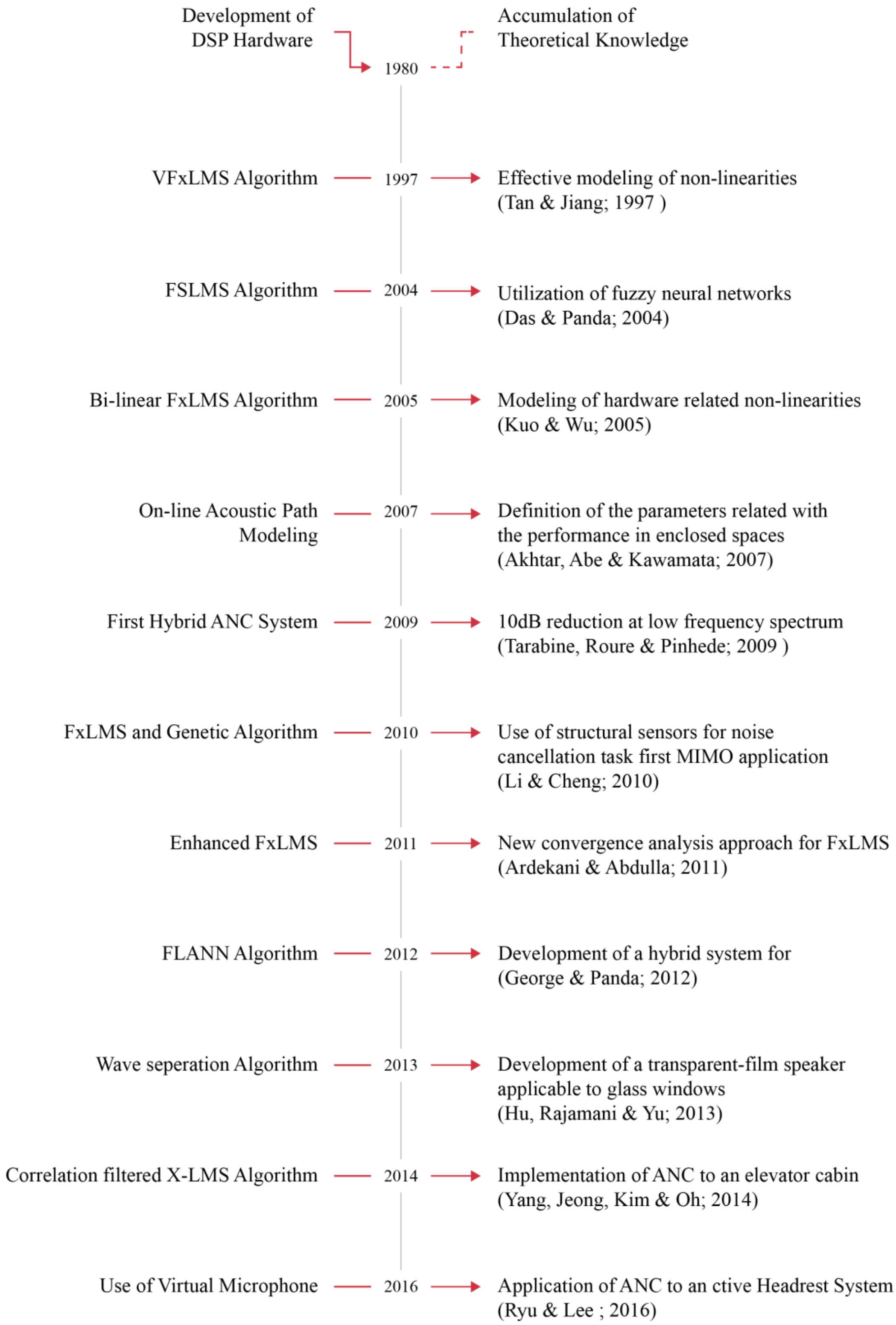

Figure 2: Benchmark studies in ANC Literature.

CHAPTER 3

THEORY

One of the major concerns of the noise control strategies is related with the characteristics of the noise itself in order to define the system performance criterion. Different system architecture settings, different algorithms and variety of system components are available for such an application. However, in order to ensure usability, efficiency and robustness; subject of the problem, environmental noise and parameters used for evaluation of environmental noise should be examined in detail. Moreover, as used algorithms highly effect the system performance; implemented algorithm should match with the characteristics of the noise and processing capacity of the ANC system. Hence, control action to be utilized should be selected considering the available equipment.

In this chapter, environmental noise is defined and related parameters for the evaluation and assessment of the environmental noise are presented. Moreover, widely used active noise control strategies are presented to propose the most suitable system architecture and control strategy.

3.1. ENVIRONMENTAL NOISE AND EVALUATION PARAMETERS

Noise can be defined as the unwanted and disturbing sound perceived. As there is no physical difference between sound and noise, main distinction is made by the perception. In this regard, noise seems subjective and context-dependent. However, it is common practice to define noise as audible acoustical energy that adversely effects, or may affect, the physiological and psychological well-being of people (Berglund & Lindvall, 1995).

Due to its subjective nature, it has become inevitable to measure noise in an objective way. Hence, measurement methods are declared clearly by the internationally recognized standards. Although there are slight differences between the methods proposed in standards, L_{eq}, the equivalent continuous sound pressure level for a given period is primarily used for the assessment of noise. In order for L_{eq} to be calculated, first sound pressure level, L_p should be known; calculated or measured;

$$L_p = 20\log\frac{P_l}{P_r}. \qquad (3.1.1)$$

where,

- P_l: *sound pressure in N/m² (Pa).*
- $P_r = 0.00002\ N/m^2$, *reference sound pressure in N/m² (Pa).*

As the sound pressure varies with time, (3.1.1) can be expressed as;

$$L_p(t) = 20\log\frac{P_l(t)}{P_r}. \qquad (3.1.2)$$

L_{eq} can be calculated as follows;

$$L_{eq} = 10\log\left[\frac{1}{T}\int_{o}^{T} 10^{L_p(t)/10}dt\right]. \qquad (3.1.3)$$

L_{eq}, which is used as the main indicator for noise assessments also gives information about the extremes of a noise event. L_{max} and L_{min} are the highest and the lowest sound pressure levels recorded during a noise measurement.

L_{peak} is the maximum value obtained during the measurement. It differs from L_{max} which is the RMS value while L_{peak} is the crest of the sound pressure within the measuring period.

Apart from equivalent continuous sound pressure level; L_n, a statistical parameter, can be used for presenting the noise levels exceeded for the n% of the measurement time. As an example, L_{90} = 76.5 dB indicates that for the 90% of the measurement period, 76.5 dB is exceeded.

Another important approach for analyzing the measurement data is using the octave bands. Utilizing the octave bands, frequency spectrum can be divided into frequency bands in order to examine the spectral components of the measured signal. When the audible frequency range (20 hz – 20000 hz) is concerned, approximately 11 octave bands are present. An octave band is named with its central frequency and covers the range with a highest frequency as twice as much the lower frequency. As an example, 250 hz octave band covers the frequency range from 176.7 hz to 353.5 hz. When a more detailed analysis is required, 1/3 octave bands can be used instead of octave bands. Lower and upper frequency of a 1/3 octave band with a central frequency f_c can be calculated by (3.1.4) and (3.1.5).

$$f_c^{low} = f_c / 2^{1/6}. \tag{3.1.4}$$

$$f_c^{high} = 2^{1/6} \times f_c. \tag{3.1.5}$$

As an example, 250 hz 1/3 octave band covers the frequency range from 222.7 hz to 280.6 hz.

1/3 octave bands values of L_{eq}, L_{max}, L_{min} and L_{peak} as well ass L_n values are used for the evaluation and assessment of environmental noise measured and for the valuation of the test cases conducted throughout this study.

3.2. ACTIVE NOISE CONTROL THEORY

Active noise cancellation can be expressed as reduction of noise using electro acoustic means. Unwanted noise is reduced by generating the anti-noise signal and reproducing the generated anti-noise signal in the same acoustic environment where the original noise is present. Hence by superposing the original noise and anti-noise signals, reduction can be achieved. As a brief summary, ANC is destructive interference of harmonic sound waves. However, noise is rarely harmonic.

In this regard, although theory is very straightforward, there are limitations in the applications of ANC in different fields. Anti-noise signal should be produced fast enough to result in perfect destructive superposition of noise and control signal. Since the noise is complex, processing noise and anti-noise as a collection of harmonic signals is very crucial and requires high performance. Moreover, generated control signal should be transformed to acoustic waves with remarkable fidelity. Hence, performance of an active noise control system is highly dependent to control system that generates the anti-noise signal, electro-acoustic system components (sensors and transducers), as well as proper choice of control strategy in accordance with noise source, available software and hardware.

Control systems to be employed for such a task should be composed of perfect combination of A/D (analog to digital) and D/A (digital to analog) converters with sufficient precision, a fast processor that can conduce the required calculations fast enough, and an algorithm suitable for the characteristics of the noise and use area of the system.

Electro-acoustic part of an active noise cancellation system is generally composed of acoustic and non-acoustic sensors, loudspeakers, pre-amplifiers and amplifiers. Each of these elements should be carefully selected to ensure that the system is capable of working at the required ambient conditions and powerful enough to cancel out the noise mentioned.

Apart from the properties of the system components, time dependent variations in the system requires that the controller should adapt itself to the changing characteristics of the noise as well as environmental conditions. Hence, controller should be able to account for the changes in secondary path properties.

Active noise cancellation systems can be classified into two groups in terms of their control architecture as feedforward and feedback. In the forthcoming part of this section, these two approaches compared in order to determine the proper control strategy in regard with traffic noise and available computation power and hardware.

In the context of ANC, difference between feedforward control strategy and feedback control strategy is important as the difference substantially affect the components used in the system, hardware cost and overall performance.

The most important difference between two approaches is the way of capturing the original noise in order to calculate the anti-noise. Feedforward systems employs an extra microphone to capture the reference signal (original noise) while feedback systems do not. However, adaptive feedback systems still need to supply a reference signal to the controller. Hence, they use the signal from secondary microphone (error microphone at the control point) to estimate the original noise.

3.2.1 FEEDFORWARD ACTIVE NOISE CONTROL

Schematic of a generic, single channel, feedforward active noise cancellation system is presented in Figure 3. A generic single channel feedforward active noise cancellation system consists of a reference microphone, an error microphone, a loudspeaker, an amplifier and an adaptive controller. In order to generate anti-noise signal, the input from reference microphone is processed by the adaptive controller.

Block diagram of a generic feed-forward active noise cancellation system is shown in Figure 4.

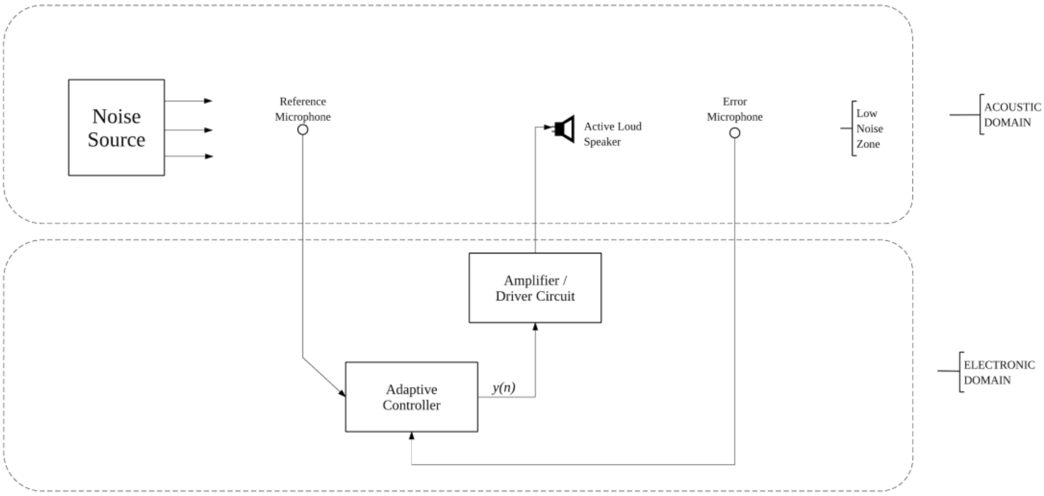

Figure 3: Schematic of a generic feedforward active noise cancellation setup.

- $C(z)$*: Transfer function of the adaptive controller:* represents the input-output relationship of the controller on z-domain.
- $P(z)$*: Transfer function of the primary path:* acoustic path from reference microphone to error microphone, which represents the input-output relationship of the acoustic path reference microphone to error microphone on z-domain.
- $S(z)$*: Transfer function of the secondary path*: electro-acoustic path from the output of the controller to the output of the error microphone, which represents the input-output relationship of the series of paths from output of the controller to the output of the error microphone on z-domain.

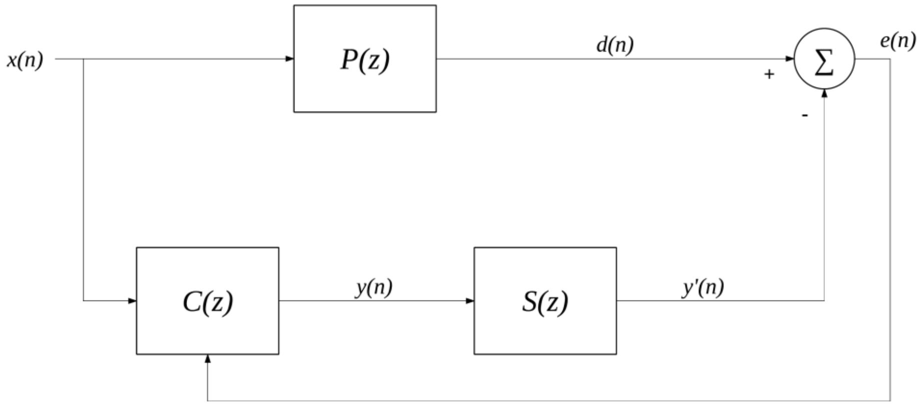

Figure 4: Block diagram of a generic feed-forward active noise cancellation system.

- *x(n):* noise to be cancelled, captured by reference microphone.
- *e(n):* residual noise, captured by error microphone.
- $y(n)$*:* control signal, generated by adaptive controller.
- n*:* denotes the time index.

Generated control signal $y(n)$ is fed to amplifier and loudspeaker for the cancellation task. Error and reference microphones are used to input the measured acoustic noise $e(n)$ and noise to be cancelled $x(n)$, respectively, to adaptive controller. Adaptive controller tries to minimize measured acoustic noise.

Decomposing the block diagram of the controller, a more detailed version of the system representing the adaptive controller is shown in Figure 5, where $A(z)$ is the filter coefficients calculated. Presented system uses a standard LMS (Least Mean Squares) algorithm which tries to minimize a cost function.

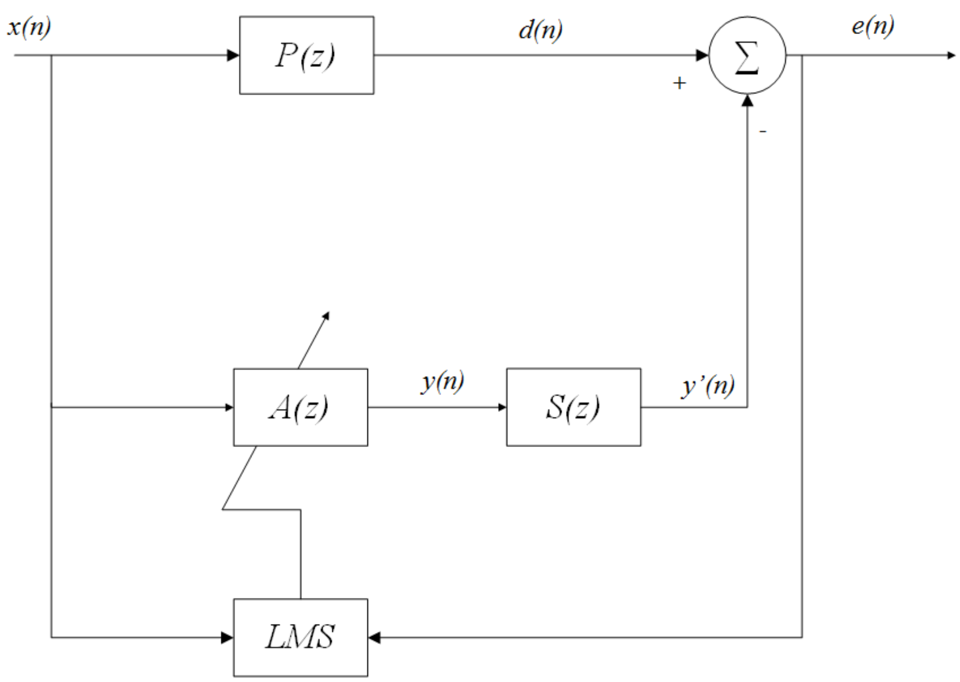

Figure 5: Decomposed controller representation of a generic, single channel feedforward system.

For an ideal control task, error signal $e(n)$ should be minimized. Using z-transform, error signal can be expressed as;

$$E(z) = [P(z) - S(z)A(z)]X(z). \tag{3.2.1}$$

For the ideal cancellation task;

$$E(z) = 0. \tag{3.2.2}$$

Replacing $E(z)$ in (3.2.1) with (3.2.2);

$$A(z) = \frac{P(z)}{S(z)}. \tag{3.2.3}$$

$P(z)$ and $S(z)$ should be modeled in real time by the filter. Hence, it can be stated that, performance of an active noise cancellation system is highly dependent to the path $P(z)$ and secondary path $S(z)$. Morgan states that, the integration of the secondary-path transfer function into a controller using the standard LMS algorithm causes instability as the error signal is not correctly aligned in time with the reference signal due to the secondary path effects (Morgan, 1980). As a solution to this problem, filtered-X LMS (FXLMS) algorithm is proposed by independent studies (Widrow, Shur, & Shaffer, 1981) (Burgess, 1981). Block diagram of an active noise control system working with FXLMS algorithm is presented in Figure 6.

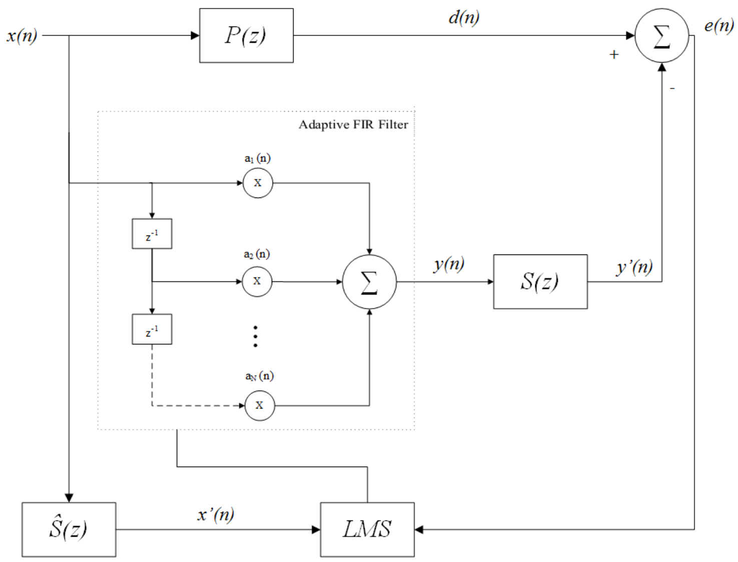

Figure 6: Block diagram of an active noise control system working with FXLMS algorithm.

According to the block diagram presented, residual error $e(n)$ can be expressed as;

$$e(n) = d(n) - s(n) * [a^T(n)x(n)]. \tag{3.2.4}$$

where,

- $s(n)$: impulse response of the secondary path $S(z)$.
- $a(n) = [a_0(n)\ a_1(n) \dots a_{L-1}(n)]^T$, coefficient vector.
- $x(n) = [x(n)\ x(n-1) \dots x(n-L+1)]^T$, reference signal vector.
- L: order of the filter.

As the filter minimizes the measured squared error $e^2(n)$, a cost function $\xi(n)$ can be written as;

$$\xi(n)) = e^2(n). \tag{3.2.5}$$

Using gradient descent approach with a step size of μ;

$$a(n+1) = a(n) - \frac{\mu}{2}\nabla\xi(n). \tag{3.2.6}$$

using (3.2.5);

$$\nabla\xi(n) = \nabla e^2(n)) = 2[\nabla \mathrm{e(n)}]e(n). \tag{3.2.7}$$

from (3.2.4);

$$\nabla e(n) = -s(n) * x(n)] = x'(n). \tag{3.2.8}$$

where,

- $x'(n) = [x'(n)x'(n-1) \dots x'(n-L+1)]^T$
- $x'(n) = s(n) * x(n)$.

Hence $\nabla\xi(n)$ becomes

$$\nabla \mathrm{\xi(n)} = -\mathrm{2x'(n)e(n)}. \tag{3.2.9}$$

Substituting (3.2.9) into (3.2.6), filter coefficients can be obtained using FXLMS algorithm as;

$$a(n+1) = a(n) + \mu x'(n)e(n). \tag{3.2.10}$$

Although presented FXLMS algorithm is widely used for ANC applications, key factor for the performance is highly dependent the step size of the algorithm. Moreover, as the feedforward principle uses a reference microphone which may capture anti-noise signal from the control speaker resulting in the poor referencing of the noise to be reduced. Unwanted acoustic feedback may result in decrease in the performance of the system.

Acoustic feedback problems regarding the ANC systems can be solved by use of high directivity speakers and microphones. Also, IIR filters with relatively smaller step sizes or feedback neutralization methods may be utilized.

FXLMS algorithm used as a part of feedforward control strategy offers the potentials of stability, low computational power and high reduction performance.

3.2.2. FEEDBACK ACTIVE NOISE CONTROL

As an alternative to feedforward case in Figure 7, schematic of a generic, single channel feedback active noise cancellation setup is presented. Main difference between a single channel feedforward systems and feedback systems is the number of microphones used due to the feedback architecture of the system. Feedback active noise control system does not require a reference microphone as the basic principle is using the estimate of the reference signal with the error microphone in order to produce anti-noise.

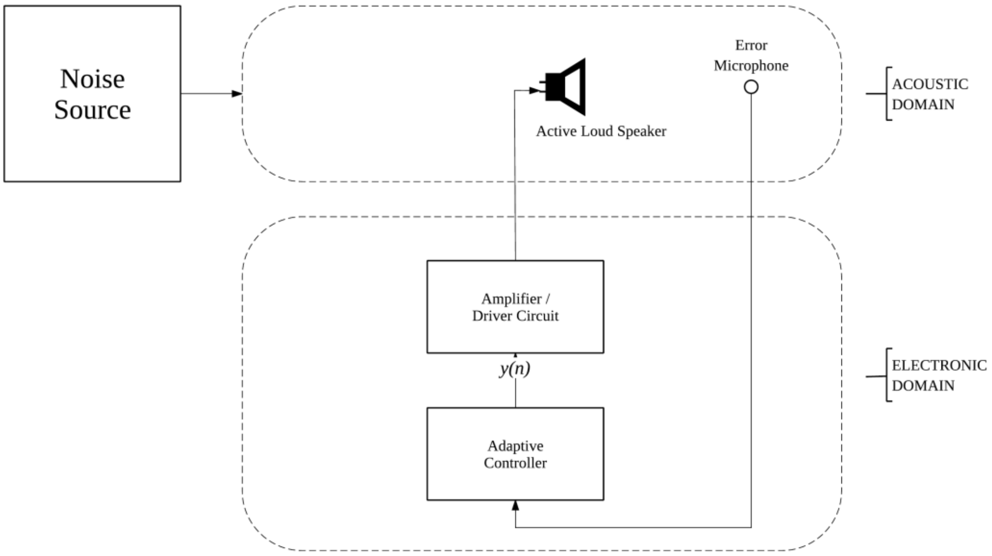

Figure 7: Schematic of a generic, single channel feedback active noise cancellation setup.

Block diagram of a generic feedback active noise cancellation system is shown in Figure 8. As opposed to feedforward system architecture, only $e(n)$, residual error is fed to the controller.

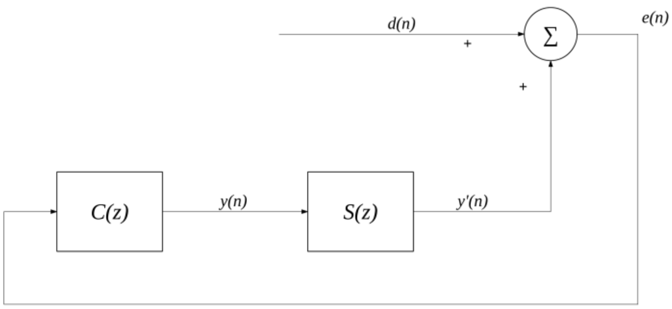

Figure 8: Block diagram of a generic feedback active noise cancellation system.

Although there is no direct reference signal input, for the calculation of the anti-noise, estimate of the reference input should be calculated. Decomposing the block diagram of the controller, a more detailed version of the system representing the adaptive controller for the feedback architecture is shown in Figure 9.

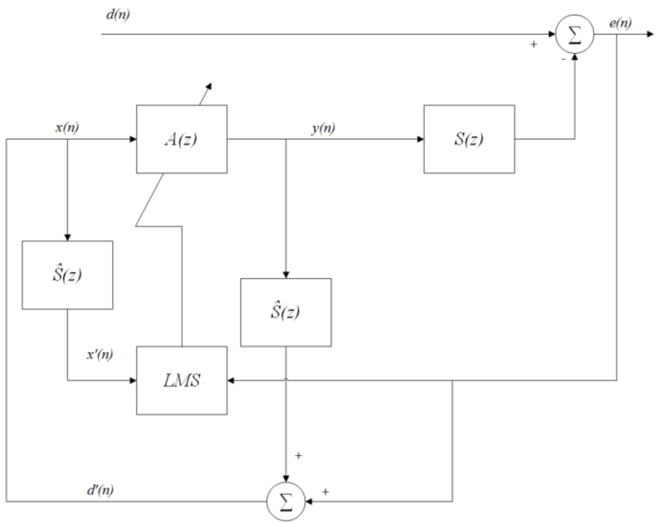

Figure 9: Decomposed controller representation of a generic, single channel feedforward system.

Using the same notations, noise to be cancelled $D(z)$ can be written as;

$$D(z) = E(z) + S(z)Y(z). \tag{3.2.11}$$

Assuming that the secondary path $S'(z)$ is estimated perfectly;

$$S'(z) \approx S(z). \tag{3.2.12}$$

hence,

$$X(z) = E(z) + S'(z)Y(z). \tag{3.2.13}$$

Kuo and Morgan (Kuo & Morgan, Active Noise Control Systems-Algorithms and DSP Implementations, 1996) states that, if $S'(z) = S(z)$ the transfer function $H(z)$ of feedback ANC from $d(n)$ to $x(n)$ can be expressed as;

$$H(z) = \frac{E(z)}{D(z)} = 1 - S(z)A(z). \tag{3.2.13}$$

Hence, under ideal conditions the adaptive feedback ANC system is identical to the feedforward system (Kuo & Morgan, Active Noise Control: A Tutorial Review, 1999).

Although for ideal cases, theoretically, feedforward and feedback FXLMS active noise cancellation systems are similar, when the application is considered they have their advantages and disadvantages.

Feedback systems are more applicable for the cases where placement of a reference microphone is impossible or not preferable. Feedforward systems require placement of an extra microphone (reference microphone). However, they are less complex computationally as feedback systems need to estimate the reference noise $x'(n)$, using secondary path estimate $\hat{S}(z)$, which requires an extra convolution operation for each sample. Although feedforward FXLMS algorithms are prone to acoustic feedback, application case subjected to this study does not necessitate robustness of the algorithm in terms of acoustic feedback compensation, due to the relatively long distance of a potential reference microphone position.

3.2.3. NON-LINEARITIES IN ANC

FXLMS Algorithm is widely used for different application cases for active noise cancellation both as a part of feedback and feedforward control approach. However, FXLMS algorithms can easily get unstable when nonlinearities are present.

There are different factors that may cause nonlinearities for an ANC application. Reference and error microphones can get saturated if they are exposed to high sound pressure levels during operation. As a result, measured voltage may not reflect the actual sound pressure level.

Similarly, loudspeaker emitting the control signal may not be able to reproduce the driven electric signal or the amplifier that is driving the loudspeaker may be overloaded. Hence, the actuating elements can cause nonlinearities.

Ageing of the system components should be carefully considered, as by the time, electro-acoustic components may cause loss of precision and decrease in overall system performance.

Nonlinearities may adversely affect convergence speed of the algorithm and system performance; even cause instability in extreme cases.

Although there are known weaknesses of FXLMS algorithm, especially in terms of nonlinearities, some negative effects of the nonlinearities may be restrained with proper implementation of high pass filters and by limiting the output of the system.

As mentioned before, at the second chapter of this work, which is dedicated to state of the art, with the emergence of faster processors, algorithms that can compensate for the nonlinearities in active noise control are already developed.

As the scope of this study is to offer a new method for controlling environmental noise in open spaces of buildings as well as proving the applicability of the ANC methods for the mentioned case. Comparison of the feedback and feedforward FXLMS algorithms shows that, regarding the hardware available and computational power required to run the system, feedforward control strategy employing FXLMS algorithm to calculate the control signal is preferred for the proposed application. Feedforward FXLMS algorithm is robust enough to serve and more economical in terms of computational cost.

CHAPTER 4

METHOD

Throughout this chapter, characteristics of the traffic noise is examined in detail using the measurement data obtained from field. This chapter introduces the design of proposed ANC system prototype as well as used algorithm, device settings and measurement standards and test setup. Another contribution of this chapter is to the determination of the test cases, as the measured noise data is an important indicator of the noise characteristics that the system tries to decrease.

4.1. ANALYSIS OF ENVIRONMENTAL NOISE CHARACTERISTICS

In this thesis, different than most of the ANC applications, outdoor traffic noise is concerned. The general features of outdoor traffic noise are related with speed of the traffic, asphalt lining of the road, traffic flow and vehicle characteristics. As a generalization, traffic noise can be considered as unsteady noise in a relatively narrow frequency band. Due to the unsteadiness, in order to exemplify the major features of traffic noise, noise data is collected from the field measurements.

In this regard, noise measurements were conducted at three possible application areas in Ankara, Turkey. Measurement points are selected to evaluate the actual case of noise characteristics at buildings classified as ‘very sensitive buildings’ and ‘sensitive buildings’ according to regulations currently in force. Each of the cases represents different types of usage which are hospitals, workplaces and schools. Selected measurement points and corresponding buildings are:

– *Medicana Hospital – Very sensitive usage area*
– *Ministry of Science, Industry and Technology – Sensitive usage area*
– *Çankaya University – Very sensitive usage area*

As presented in Figure 10, buildings of interest are all located next to Dumlupınar Boulevard, which is one of the main axis of Ankara in East-West direction throughout the city center. Leaving the centrum, this road evolves to D-200 highway, which connects Ankara to western and south westerns neighbors.

Figure 10: Location of selected building for noise measurement.

Measurements are conducted according to standards ISO 1996-1 and ISO 1996-2. Hence, measurement points, presented in Figure 11, are selected in accordance with the related standards. Each measurement is conducted for ten minutes. Svantek SVAN 958 Type 1 Sound & Vibration Analyzer (S/N: 28479) was utilized for the noise measurements. Weather data during the measurements are obtained from weather station located at Middle East Technical University, Physics Department as;

- Temperature: 19° C
- Humidity: 45%
- Wind Speed: 2.5 km/s

Figure 11: Location of measurement points for each selected building.

Results of the of the measurement noise measurements held at Medicana Hospital, Ministry of Science, Technology and Technology and Çankaya University are presented in Table 1, Table 2, and Table 3, respectively. Ln Spectra results for all measurement cases are presented in Table 4.

Table 1: Noise measurement results for Medicana Hospital.

Filter	Detector	L_{peak}	L_{max}	L_{min}	L_{eq}
		(dB)			
Lin	**Fast**	99.7	90.8	73.8	79.6
Lin	**Impulse**	99.7	91.9	75.6	79.6
A	**Impulse**	96.5	87.8	67.8	73.3

Table 2: Noise measurement results for Ministry of Science, Industry and Technology.

Filter	Detector	L_{peak}	L_{max}	L_{min}	L_{eq}
		(dB)			
Lin	**Fast**	103.8	97.6	68.7	77.9
Lin	**Impulse**	103.8	99.5	71.0	77.9
A	**Impulse**	100.6	88.1	59.1	66.7

Table 3: Noise Measurement Results for Çankaya University.

Filter	**Detector**	**L_{peak}**	**L_{max}**	**L_{min}**	**L_{eq}**
		(dB)			
Lin	**Fast**	97.9	90.2	60.8	76.0
Lin	**Impulse**	97.9	91.0	63.2	76.0
A	**Impulse**	90.0	78.8	54.5	70.1

Table 4: L_n Spectra results for noise measurement points.

Measurement Points	**Ln Spectra (dB)**									
	L_{01}	**L_{10}**	**L_{20}**	**L_{30}**	**L_{40}**	**L_{50}**	**L_{60}**	**L_{70}**	**L_{80}**	**L_{90}**
Medicana Hospital	85.7	81.6	80.4	79.7	79.2	78.7	78.3	77.8	77.3	76.5
Ministry of Science, Industry and Technology	85.7	80.2	78.6	77.4	76.5	75.6	74.8	74.0	73.1	72.0
Çankaya University	84.0	79.0	77.1	75.8	74.8	73.8	72.9	72.0	71.0	69.3

Presented results show that measured noise at Medicana Hospital and Çankaya University is higher than the threshold values stated by the related regulations (Çevresel Gürültünün Değerlendirilmesi ve Yönetimi Yönetmeliği, 2010) while numeric value measured at Ministry of Science, Industry and Technology is below the threshold but very close to the limit. Moreover, measured background noise is higher than the limiting value for all three cases.

Regarding the characteristics of the measured noise, for all three cases, values measured with detector settings of ‘impulse’ and ‘fast’ are so close to each other that traffic noise can be assumed to be non-impulsive.

Examining the measurements in 1/3 octave frequency bands, which are presented in Figure 12, Figure 13 and Figure 14 for three cases, noise measured in these points are not tonal. When the spectral components are compared, it can be seen that low and mid frequency components dominate the noise characteristics, by nature, holding a substantial part of spectral energy density.

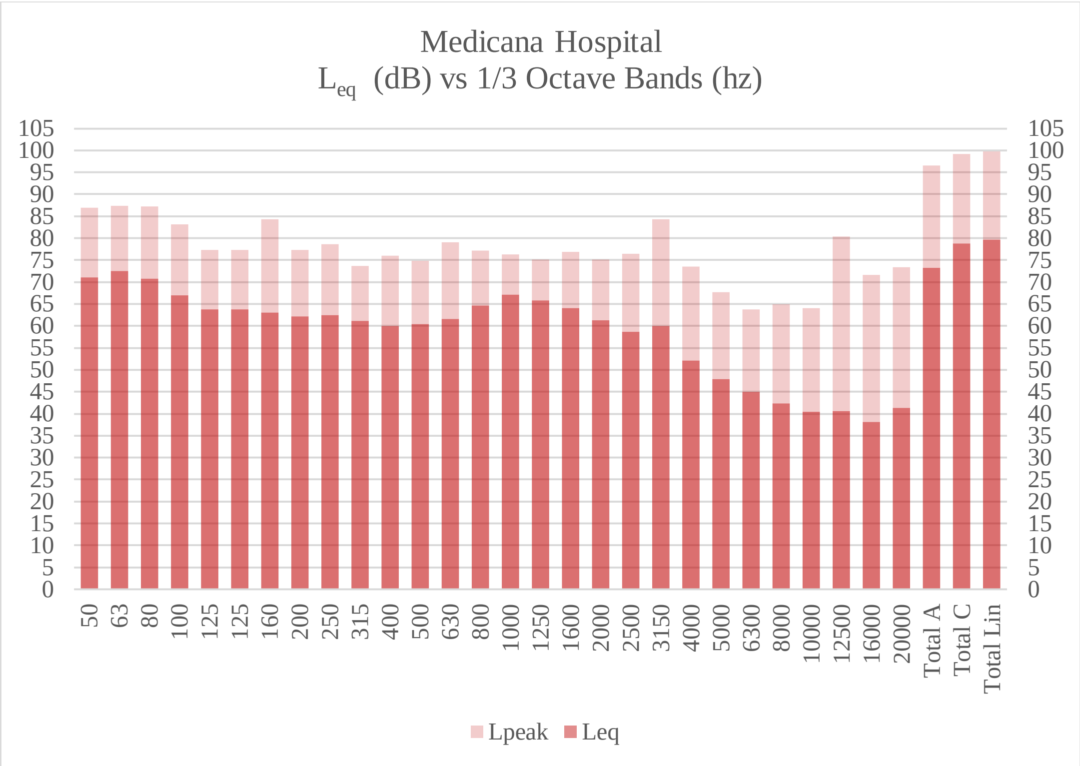

Figure 12: 1/3 octave band noise measurement results for Medicana Hospital.

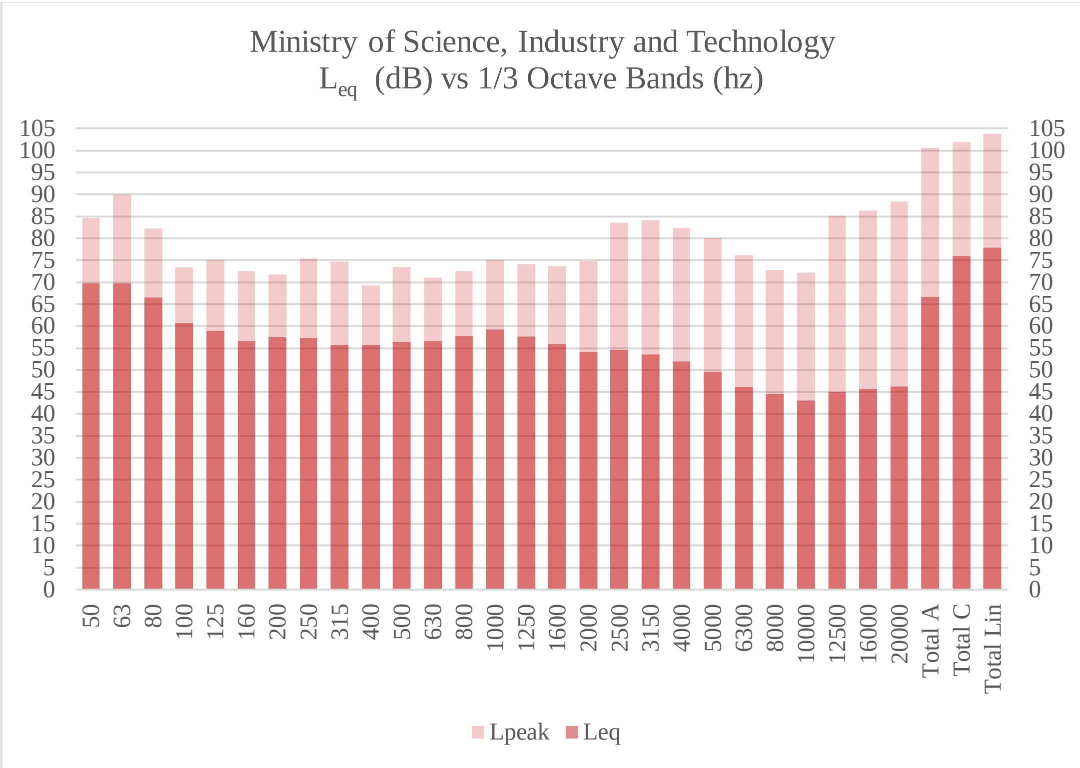

Figure 13: 1/3 octave band noise measurement results for Ministry of Science, Industry and Technology.

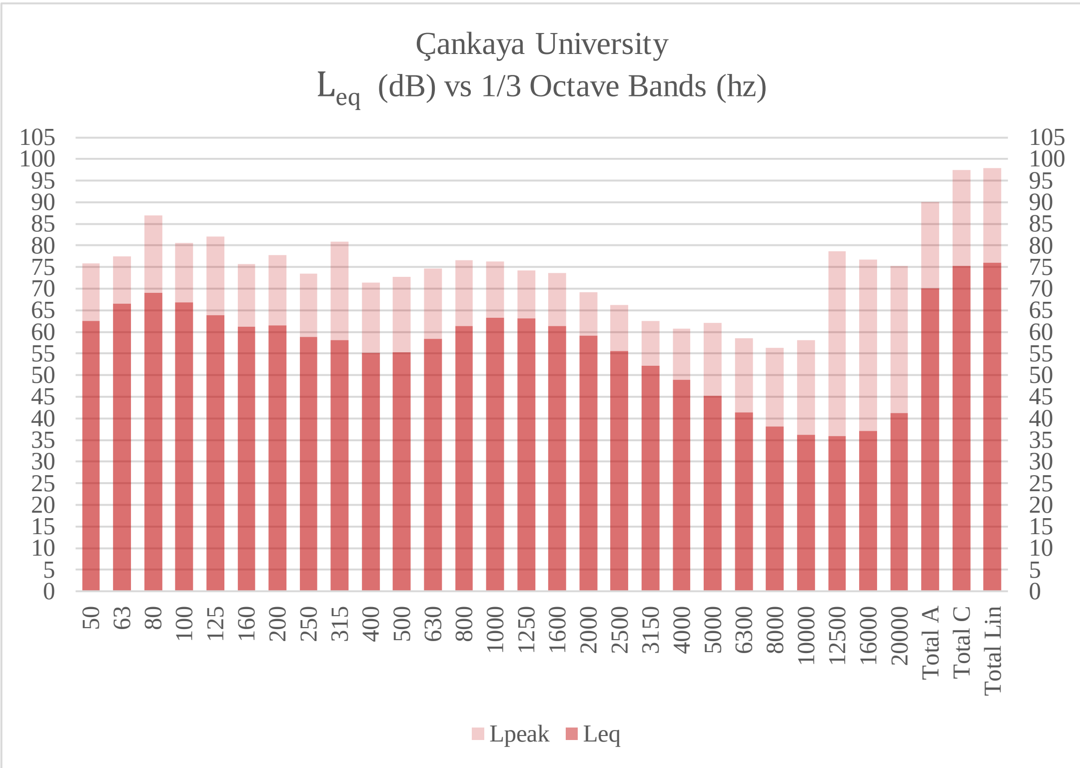

Figure 14: 1/3 octave band noise measurement results for Çankaya University.

Logger data for each measurement are shown in Figure 15, Figure 16 and Figure 17. Fluctuations and irregularities present in logger data shows that measured noise is unstable as the amplitudes of the recorded signals do not show any tendency to get stabilized by the time.

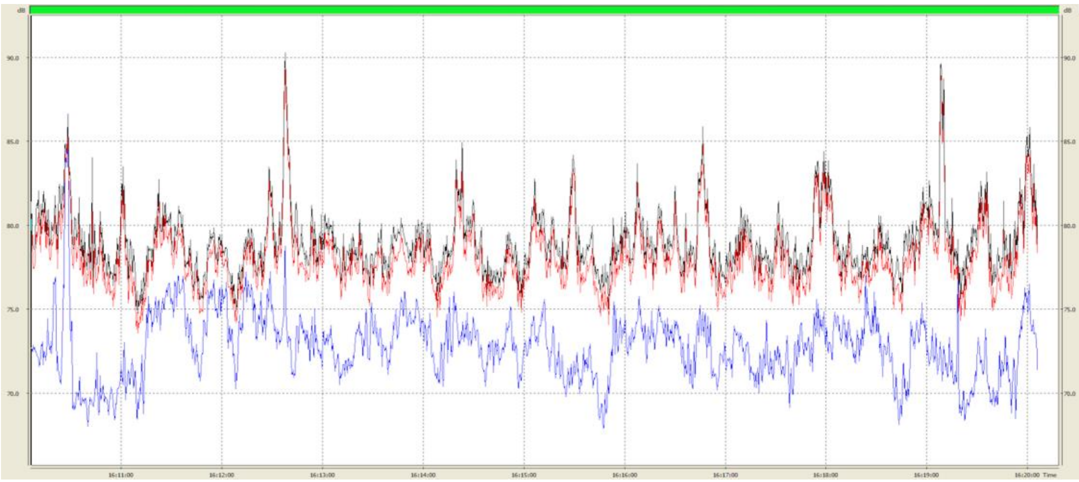

Figure 15: Logger data obtained during noise measurement held at Medicana Hospital.

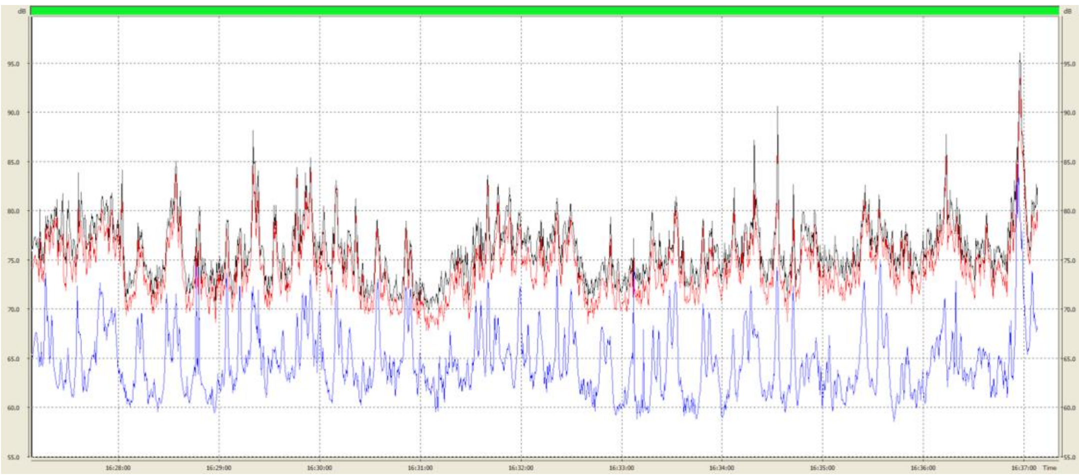

Figure 16: Logger data obtained during noise measurement held at Ministry of Science, Industry and Technology.

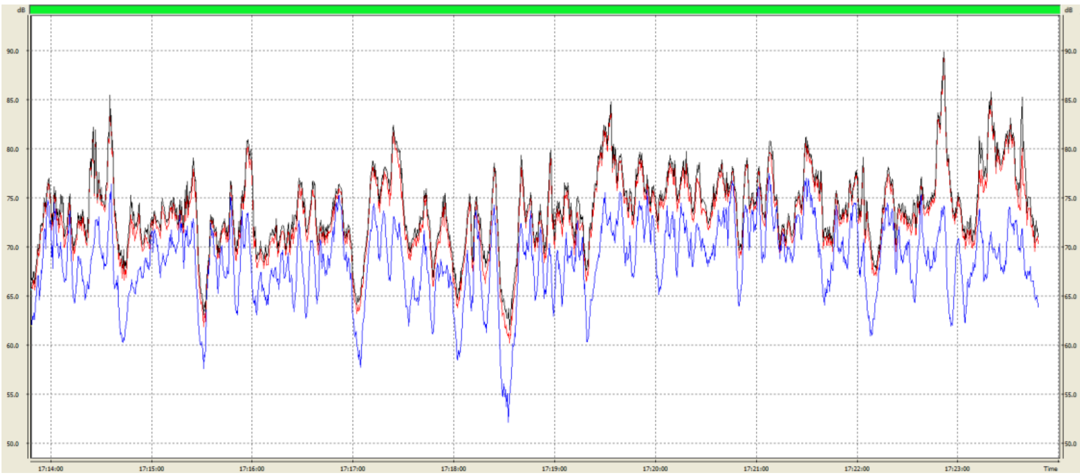

Figure 17: Logger data obtained during noise measurement held at Çankaya University.

Noise measurements and analysis of the results show that environmental noise, which is mostly composed of traffic noise for the examined cases, is unsteady and wideband. It can also be seen that, contribution of noise to low and mid frequency range is significant.

This results imply that, a system for the control of environmental noise should be able to reduce broadband, low to mid frequency, unsteady, complex noise. Although impulsiveness is not the main concern for the success, in terms of stability requirements, system should be able to handle impulsive disturbances in order to keep the stability.

An important requirement of a validation test is the standardization of the test cases in order for the comparableness of the results. Some of the standard test signals globally accepted and used by test and verification of electronic and acoustic systems are white noise, pink noise, brown (red) noise and grey noise. Although all four alternatives are wideband and pseudorandom, main difference between them is the weighting of the spectral components. Broadband noise signals can be used to test the effective frequency range and frequency response of the system in the case of random disturbances. Broadband signals are widely used for challenging the systems for unpredictable disturbances. As an example, broadband noises can be utilized for simulating the effects of fast flowing heavy traffic noise. White noise is the unweighted broadband noise and in terms of comparability, it is the most commonly used broadband test noise.

As an alternative to broadband versions of the test tones, monotonic test signals can be employed as well, to test the additivity characteristics of the system. Examples of monotonic test signals are sine waves, square waves and saw tooth wave signals, which all differ in terms of waveform. Monotonic test signals can be employed by sweeping a frequency range in time period in order to test a systems adaptability to different frequency components. As an example, collection of sweeping monotonic signals can be used to model the case of a traffic noise source gaining or loosing speed.

Examination of the traffic noise data shows that, these signals can be modeled by widely accepted, unweighted white noise to run and evaluate the proposed ANC system at the extremes. Moreover, sinusoidal sweep signals can be used to evaluate the adaptiveness of the system to changing traffic characteristics and flexibility.

4.2. DESIGN OF THE PROTOTYPE AND TEST SETUP

Schematic which represents the connection sequences, placements and the distance between the elements, of the test setup is presented in Figure 18 .Physical test setup consists of three main components; noise generator system, ANC system and measurement device.

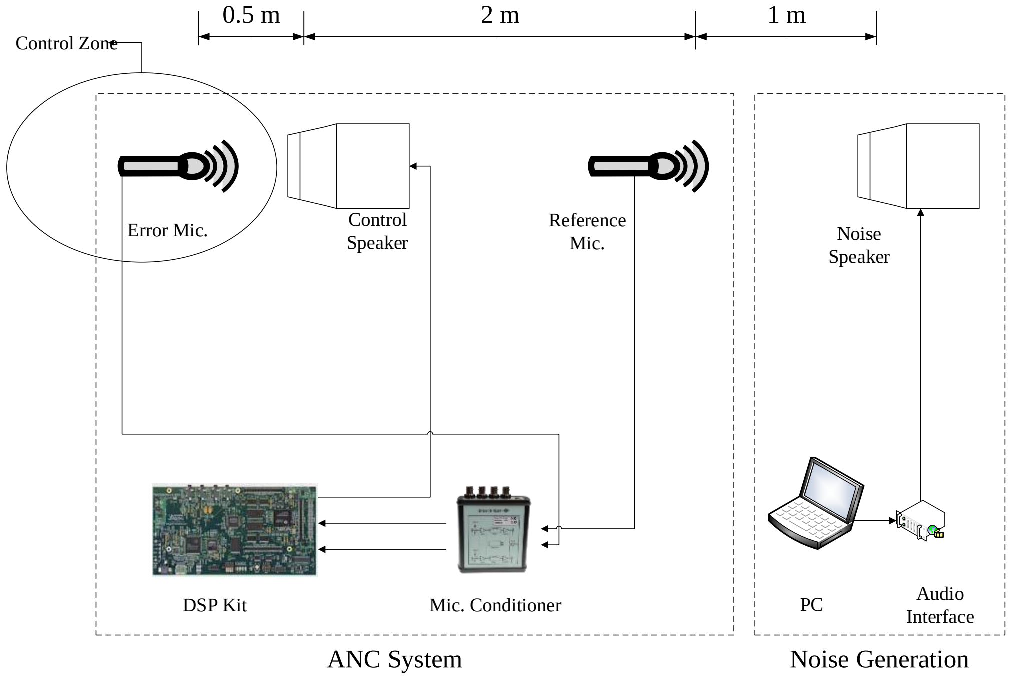

Figure 18: Schematic of the test setup.

4.2.1. NOISE GENERATOR SYSTEM

Noise generator system is required to produce broadband and monotonic noise throughout the audible range of the spectrum, 20 hz - 20000 hz, without any distortion. System should be powerful and flexible enough to simulate the characteristics of environmental noise, which was already discussed in previous chapter. In order to satisfy these requirements, a Windows based PC hosting MATLAB, a USB audio interface and a Loudspeaker are employed.

M-Audio Fast Track USB, which can be seen in Figure 19, is used as the audio interface which is connected to PC and loudspeaker. As the loudspeaker system Adam Audio A7X Reference Monitor, presented in Figure 20 is utilized. Audio interface and loudspeaker are connected with RCA cables. Input sensitivity control of the loudspeaker, tweeter, low shelf and high shelf equalizer gains are set to 0 dB.

Figure 19: USB Audio interface used as a part of the noise generator system.

Figure 20: Loudspeakers used as a part of noise generator system and ANC system.

Technical specifications of the Adam Audio A7X Reference Monitors are as follows;

Frequency response	42 hz - 50 khz
THD 90 dB/1m > 100 hz	≤0.5 %
Max SPL with sine wave acoustic 100 hz to 3 khz at 1m	≥106 dB
Max SPL per pair at 1m	≥114 dB
Crossover frequencies	2500 hz
Input impedance	30 kOhm

4.2.2. ACTIVE NOISE CONTROL SYSTEM

Components of the system is pre-defined by the used algorithm and control structure. As a feedforward FXLMS ANC system requires a reference microphone, an error microphone, a loudspeaker and a controller, system is constructed with the following components.

Exact same loudspeaker is used as in the case of noise generator system.

As the error and reference microphones, B&K 4189-A-021 ½ inch free-field pre-polarized measurement microphones with 2671 preamplifiers, which can be seen in Figure 21, are utilized. Specifications of the microphone is as follows;

Dynamic Range	16.5 - 134 dB
Frequency Range	20 - 20000 hz
Inherent Noise	16.5 dB A
Lower Limiting Frequency (-3dB):	12 hz
Pressure Coefficient	-0.01 dB/kPa
Sensitivity	50 mV/Pa
Temperature Coefficient	-0.006 dB/ºC

Figure 21: Measurement microphones used as error and reference microphone in ANC system.

In order to supply power to the measurement microphones and preamplifiers, B&K Type 1704-A-002 2-channel Battery-powered CCLD Signal Conditioner, in Figure 22, is utilized.

Figure 22: Signal conditioner used in ANC system.

Spectrum Digital TMS320C6416 1Ghz DSP Starter kit, presented in Figure 23, with 2 line inputs and 2 line outputs is used for the application of the algorithm. Specifications of the used DSP kit is as follows;

DSP	Texas Instruments
Codec	TLV320AIC23
Memory	2M x 64 on board SDRAM
Flash Memory	512kbytes on board Flash ROM
Inputs	2 x microphone, 2 x line
Outputs	2 x line, 1x headphones
Interface	4 x LEDs, 4 x switches

Detailed information on the specification of the TLV320AIC23 codec is as follows;

Sampling Frequency	8 khz - 96 khz
ADC	90db SNR Multibit Sigma-Delta
DAC	80db SNR Multibit Sigma-Delta
Bitrate	16/20/24/32

Figure 23: DSP Kit used in ANC system.

4.2.3. MEASUREMENT DEVICE, SETTINGS AND ENVIRONMENTAL CONDITIONS

Measurements are conducted with Svantek SVAN 958 Type 1 Sound & Vibration Analyzer (S/N: 28479) placed at the closest possible vicinity of error microphone. Measurement settings are chosen to reflect the behavior of noise. Capabilities of the measurement device offers 3 different setting profiles in terms of measurement filter and detector for the calculation of L_{eq}. Linear, A, C and G filter setting are provided by the device while, in combination with the filter settings, fast, slow or impact can be selected as detector. Preferred setting for the measurement profiles are presented in Table 5.

Table 5: Preferred profile settings for the measurement device.

Setting	Filter	Detector
Profile 1	A	Fast
Profile 2	C	Fast
Profile 3	Lin	Fast

Considering the measurements conducted in order to analyze the environmental noise characteristics for this study (Chapter 4.1), fast detector setting is more suitable than the other alternatives as the noise of concern is not impulsive while not stable enough to be assessed with slow detection speed.

Moreover, as the G weighting is specifically used for assessment of infrasound spectrum, Linear, A and C weightings are selected for the 3 different profiles.

During the measurements, weather data is obtained from weather station located at Middle East Technical University, Physics Department;

- Temperature: 28° C
- Humidity: 20%
- Wind Speed: 6 km/s

4.3. ASSUMPTIONS AND MEASUREMENT STANDARDS

As mentioned in the previous chapter, analysis show that environmental noise is not impulsive but unsteady and chaotic. Hence, in order to simulate this behavior during the measurements, noise generating system is tuned to produce the aforementioned noise contents for three different cases, which are assumed to represent the environmental noise.

Also, as can be seen in the specifications of the reference and error microphones, upper limit of the dynamic range of the sensors are high enough the handle the high sound pressure levels. Moreover, speaker emitting the control signal is powerful enough to produce the required sound pressure levels without being distorted.

Under these conditions, sensors and actuators used for the system can be assumed to have the dynamic range that ensures the operation without any nonlinearities.

Measurement standards followed during the measurements made throughout this study are as follows;

ISO1996-1: Acoustics - Description, measurement and assessment of environmental noise - Part 1: Basic quantities and assessment procedures

ISO1996-2: Acoustics - Description, measurement and assessment of environmental noise -- Part 2: Determination of environmental noise levels.

4.4. ALGORITHMIC IMPLEMENTATION

Implementation of the algorithm is realized using Texas Instruments Code Composer Studio 3.3.

Generated code consists of two different algorithms. First part of the code is used to measure the impulse response of the secondary path estimate $S'(n)$ using an adaptive FIR Filter while second part of the code is used for actual ANC task.

Using the DIP switch assigned, user starts the procedure for measuring the impulse response of the secondary path. This part of the code generates pseudo random noise to be emitted from the control speaker and using the input from the error microphone, FIR filter converges to resemble the impulse response of the secondary path. For each iteration of the filter, filter coefficients are saved to memory of Spectrum Digital TMS320C6416 DSP Kit. After the convergence is realized, user lifts the assigned switch to stop the procedure. Coefficient of the adaptive FIR filter present during the last iteration is saved to memory to be used as the secondary path estimate during the operation of the ANC algorithm.

Pseudo code for the secondary path impulse response is given below:

Initialize constants, buffers and arrays
While assigned dip switch is pressed
    Generate pseudo random noise sample
    Read sample from the input by reference microphone
    Output generated noise sample to loudspeaker
    Compute adaptive filter output

Compute error

Update weights of the filter

Update buffers

Second part of the implemented code is responsible for the ANC task. Pseudo code for this part is given below:

Initialize constants, buffers and arrays

While assigned dip switch is pressed

Read sample from error mic

Read sample from reference mic

Compute the anti-noise sample

Output computed anti-noise sample

Compute filtered-x version of reference sample

Update adaptive filter weights

Update buffers

Algorithms given as pseudo codes above are integrated to work on the same DSP kit, coded using C language and converted to Assembly files using TI Code Composer.

During the tests, filter lengths are selected as 128 and learning rate for the adaptive FIR filter used for measuring the impulse response of the system is selected as 1E-12 while learning rate of the feedforward FXLM algorithm set as 1E-9.

Sampling rate of the system is selected as 8 khz, which should result in control of noise up to 4 khz, as the frequency and power content of the environmental noise is mostly in the lower part of the spectrum.

Throughout this chapter, detailed analysis of the data collected from the environmental noise measurements were made and using the outcomes of the analysis, appropriate test cases are proposed.

In addition, components of the proposed system, as well as devices used for the validation of the system performance, assumptions made during validation, implemented algorithms are discussed and related measurement standards are presented.

In terms of assessment of the characteristics of the considered noise sources, important remarks of this chapter are as follows:

Traffic noise is unsteady, complex and broadband while crowded especially in the low to mid frequency range. In order to standardize the test scenarios, also considering the actual noise sources, broadband and band limited white noise and monotonic sinusoidal sweep test signals can be employed to force the limits of the system, test the stability and validate the performance.

In this regard, three cases can be used to test the performance of the ANC system. These cases are as follows:

- *Case 1: White Noise (20 hz - 20000 hz)*
- *Case 2: White Noise (20 hz - 4000 hz, Low pass with f_c=4000 hz,48db/octave)*
- *Case 3: Sine Sweep (100 hz - 1000 hz T_{sweep}=10 seconds)*

System should be able to reduce the measured noise especially in the low and mid frequency range and sustain its stability during operation.

Case 1 where the broadband white noise exists, tests the system for the most complex noise exposure. As the high frequency components are present, behavior of the noise resembles the placement of the system to the very close vicinity of the noise source. During this case, system is expected to retain its stability and achieve measurable noise reduction up to the effective working frequency of the system which is selected as 4 khz.

Case 2 tests the system for the exact working frequency range. Due to the filtered high frequency components of the noise, this case resembles the placement of the system to an application point far from the noise source while the sound pressure level of the noise is exceeding the limits. For this case, system is expected to reduce the noise measured at 1/3 octave bands approximately 5 dB to 8 dB.

Case 3 checks the system against the changing noise characteristics. Also, together with Case 1, this case tests the system for stability especially at low frequency excitations as the test signal is pure sine wave and frequency of the signal drops to the lowest working frequency where reproduction of the control signal is challenging for the control speaker. System is expected to perform better than first two cases in terms of noise reduction performance as there is no harmonic content in the noise present, which requires less computational power and less convergence time for the adaptive filter.

Next chapter presents the results of the case studies conducted with the designed prototype and highlights the important remarks.

CHAPTER 5

CASE STUDIES AND RESULTS

In order to prove the validity of the proposed system, noise measurements were conducted for three different cases which simulates the environmental noise in compliance with the real data obtained from field measurements. Photo of the designed prototype and actual test setup is presented in Figure 24. Selected test signal for each case have different intention and reflects the use cases of the prototype. Results obtained from conducted tests provide meaningful information about different aspects of the system. Throughout this chapter, results obtained from the test measurements are presented and compared.

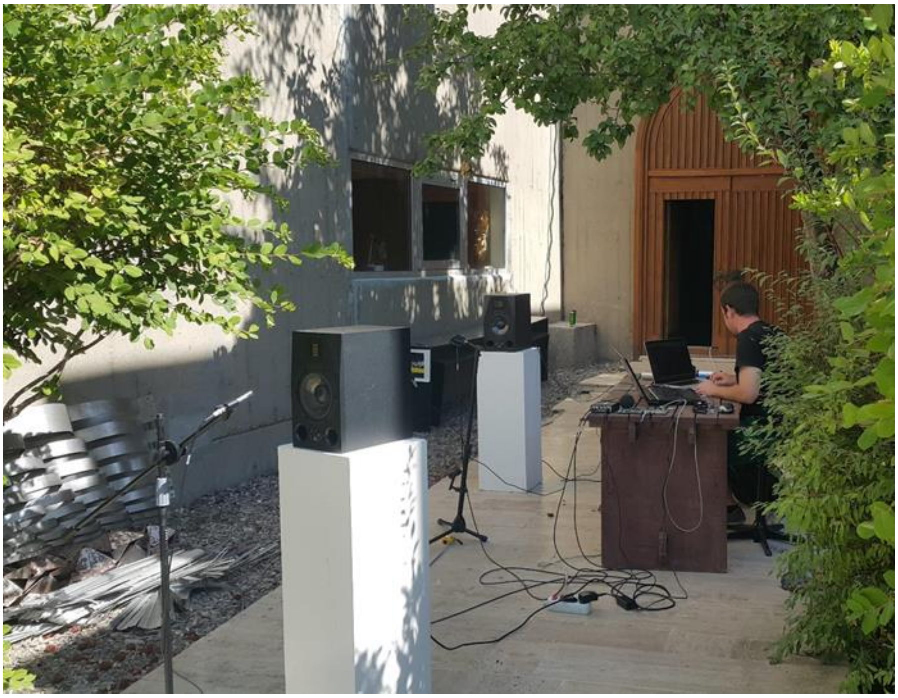

Figure 24: Prototype and test setup.

Designed test cases are proposed as the simulation of the traffic related environmental noise in accordance with the noise profiles obtained from the conducted field measurements. In order to be able to ensure comparability of the results globally, standard and widely accepted test signals which reflects the behavior of the noise observed in real cases are selected.

For each case, two sets of measurements were made. First, noise at the control point is measured while only the noise generator is active. Then, ANC system is activated and another measurement is conducted while ANC system is working. All the results throughout this chapter were presented in such a way that for each term present, three different values were reflected. 60 seconds measurements for each state of every case were taken and results are presented.

- OFF state defines the measurements held while only the noise is present.
- ON state corresponds to the measurement taken while the ANC system is active.
- DIFF stands for the difference between ON and OFF state for the corresponding term.

As the speaker of the noise generator system is not a *perfect source* in terms of frequency range; although driven signals are broadband, reproduced noise is not perfect in terms of the lowest possible reproducible frequency. As a matter of fact, lowest reproducible frequency by a speaker is directly proportional with the diameter of the low frequency woofer of the system. Hence, noteworthiness of the presented result should be considered in a frequency range starting from 100 hz.

5.1. CASE 1: WHITE NOISE (20 hz - 20000 hz)

First case resembles the use scenario of the proposed system against the fast flowing heavy traffic noise in the close vicinity of the noise source. For this case, broadband white noise was selected as the disturbance, which simulates the extreme situation that an adaptable system can be exposed. For most of the adaptive systems, hardcore conditions mean that, system works in the limit of losing stability, which may result in failure of the control action. In the case of ANC, instability results in intensification of the noise as the generated anti-noise is far away from providing the destructive interference of sound waves. Therefore, ANC system itself, becomes a noise source. Hence, it is crucial to test the system in terms of stability, before testing the system for performance.

In the close vicinity of the noise source, due to the negligible effects of air absorption on high frequency components, noise can be assumed to be present in the audible range of a healthy human. Hence no filtering is applied to the noise and broadband characteristics were preserved at 20 hz - 20000 hz.

Main results of the measurement taken for the case, where the noise is set to be 20 hz - 20000 hz white noise, are presented in Table 6. Proposed system provides only slight improvements in the overall results. Although slight reductions in L_{eq}, L_{peak} and L_{max} values are observed, improvement contributed by the system may seem low. However, when the 1/3 octave band results presented in Figure 25 and Figure 26 is examined, up to 7 dB reductions in L_{eq} are achieved especially for low and low-mid frequency range.

As the sampling frequency of the system is set to be 8 khz, efficient controllable frequency range is up to 4 khz. Hence, as expected, system is working and efficient in the frequency range that it is tuned for.

Table 6: Measurement Results of Case 1 - White Noise (20 hz - 20000 hz).

Case 1: White Noise (20 hz - 20000 hz)							
				L_{peak}	L_{max}	L_{min}	L_{eq}
Profile 1	**A Weighted**	**Fast**	**OFF**	97.81	84.37	79.83	83.82
			ON	97.47	83.61	81.84	82.69
			DIFF	0.34	0.76	-2.01	1.13
Profile 2	**C Weighted**	**Fast**	**OFF**	96.61	83.17	78.72	82.64
			ON	94.80	82.05	80.42	81.17
			DIFF	1.81	1.12	-1.70	1.47
Profile 3	**Linear**	**Fast**	**OFF**	98.97	85.44	81.01	84.97
			ON	97.88	85.35	83.18	84.12
			DIFF	1.09	0.09	-2.17	0.85

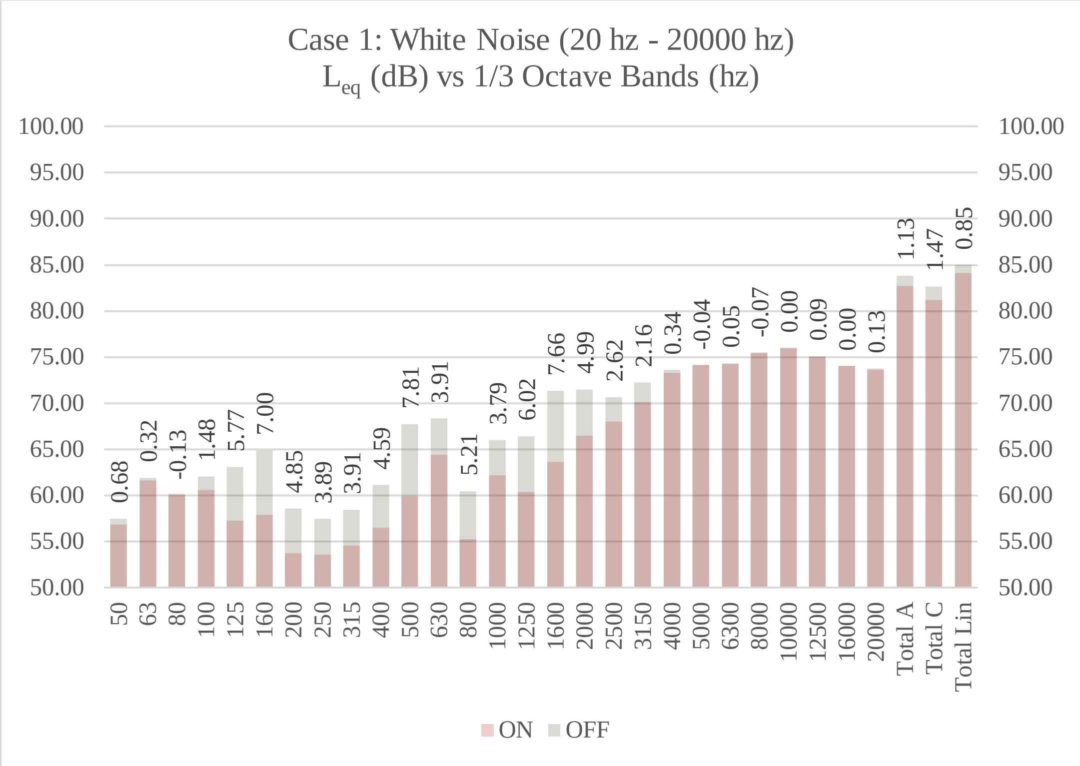

Figure 25: L_{eq} - 1/3 octave band noise measurement results for Case 1 - White Noise (20 hz - 20000 hz).

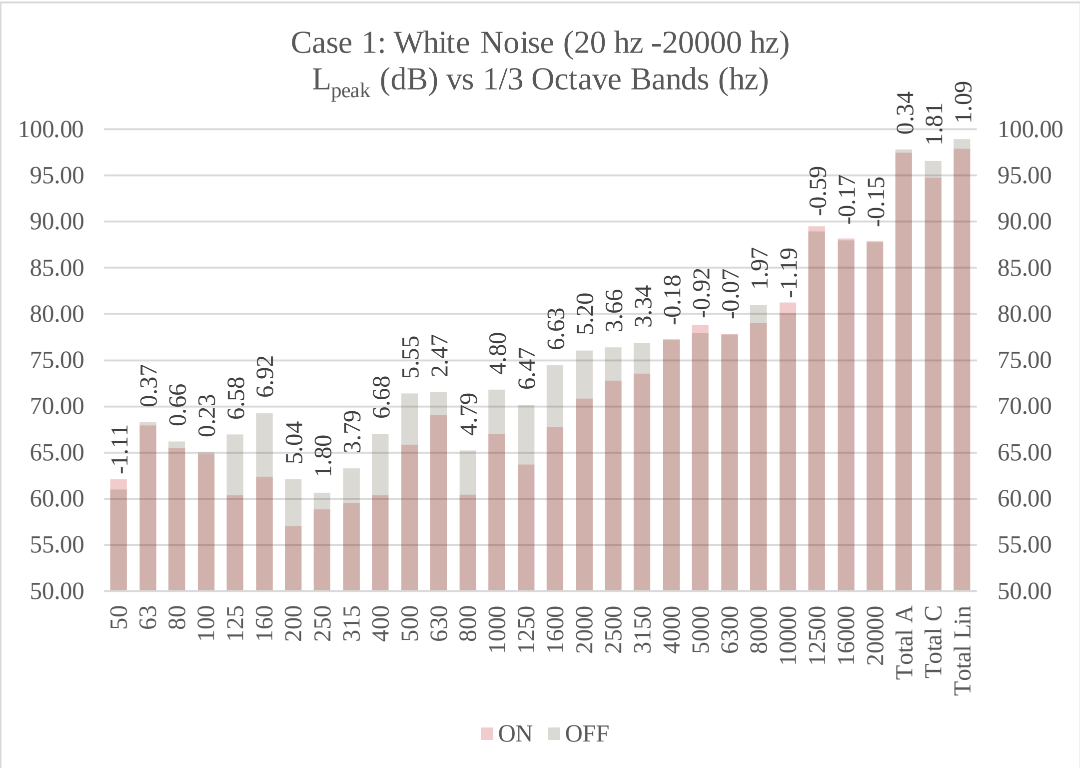

Figure 26: L_{peak} - 1/3 octave band noise measurement results for Case 1 - White Noise (20 hz - 20000 hz).

White noise, which resembles chaotic and unstable environmental noise, is the hardest case for feedforward FXLMS algorithms as FXLMS algorithms are sensitive to nonlinearities and prone to instabilities. Nevertheless, system protected its stability during operation.

Examining the reductions in the 1/3 octave L_{peak} values, it can be seen that, performance of the system is not as high as the relatively impulsive excitations. System performed better for less extreme excitations.

Results obtained in this case prove the usability of the system as a performance increasing add-on to present conventional passive barriers, which are applied on the sites that are in the close vicinity of the traffic noise.

5.2. CASE 2: WHITE NOISE (20 hz - 4000 hz)

For this case, bandlimited white noise was selected to excite the system, which simulates the fast flowing heavy traffic noise as a long distance disturbance. This case tests the performance of the system for a stand-alone application at the receiver point.

For the noise sources at a long distance to the receiver point, due to the air absorption on high frequency components, noise can be assumed to have lost energy from its high frequency components. Hence, a 48 dB/octave low pass filter with f_c=4000 hz applied to limit the frequency range of the signal to simulate the air absorption.

Having an effective range up to 4 khz, system is tested with band limited pseudo random noise in Case 2. Overall results of the measurements taken are presented in Table 7.

As the range of the produced noise is limited, higher improvements are observed. Reductions up to 4 dB in overall results are obtained in L_{peak}, L_{max}, L_{min} and L_{eq}. Moreover, when the results of the measurements presented in 1/3 octave bands are investigated, as can be seen in Figure 27 and Figure 28, an average reduction of 6 dB can be observed.

Table 7: Measurement Results of Case 2 - White Noise (20 hz - 4000 hz).

Case 2: White Noise (20 hz - 4000 hz)							
				L_{peak}	L_{max}	L_{min}	L_{eq}
Profile 1	**A Weighted**	**Fast**	**OFF**	94.39	81.30	79.79	80.43
			ON	89.96	77.26	74.65	76.12
			DIFF	4.43	4.04	5.14	4.31
Profile 2	**C Weighted**	**Fast**	**OFF**	93.39	80.81	79.27	79.95
			ON	89.05	76.52	74.22	75.43
			DIFF	4.34	4.29	5.05	4.52
Profile 3	**Linear**	**Fast**	**OFF**	93.69	81.07	79.54	80.22
			ON	89.64	76.97	74.69	75.90
			DIFF	4.05	4.10	4.85	4.32

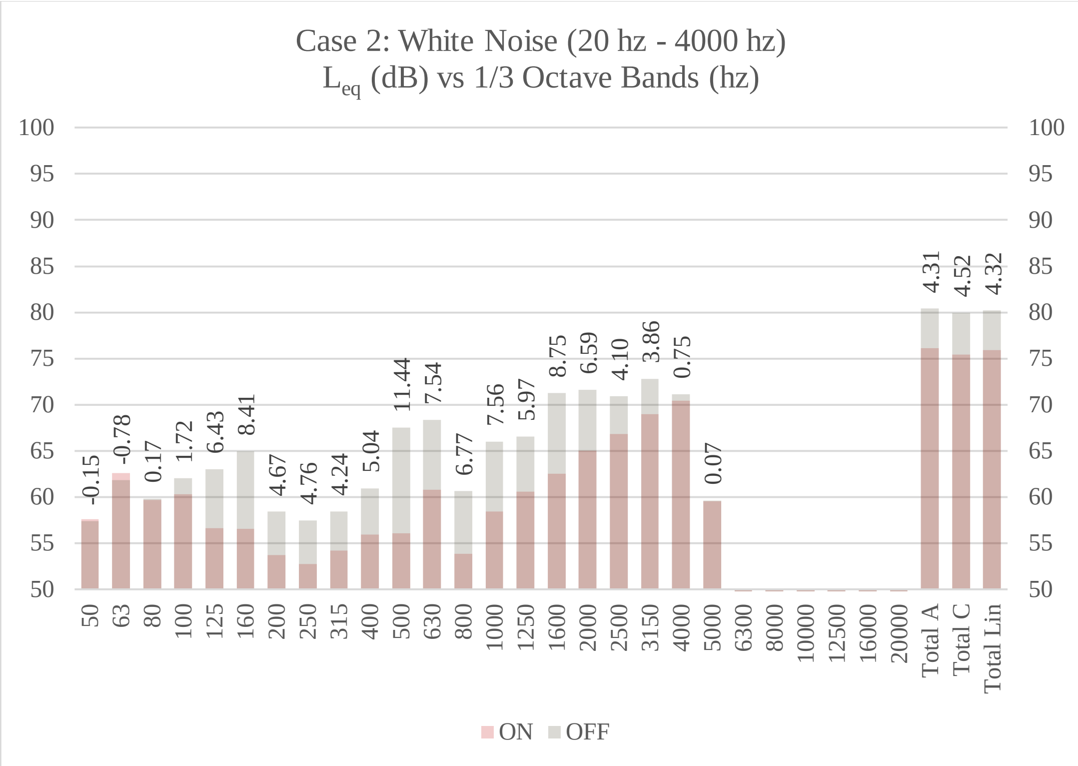

Figure 27: L_{eq} - 1/3 octave band noise measurement results for Case 2 - White Noise (20 hz-4000 hz).

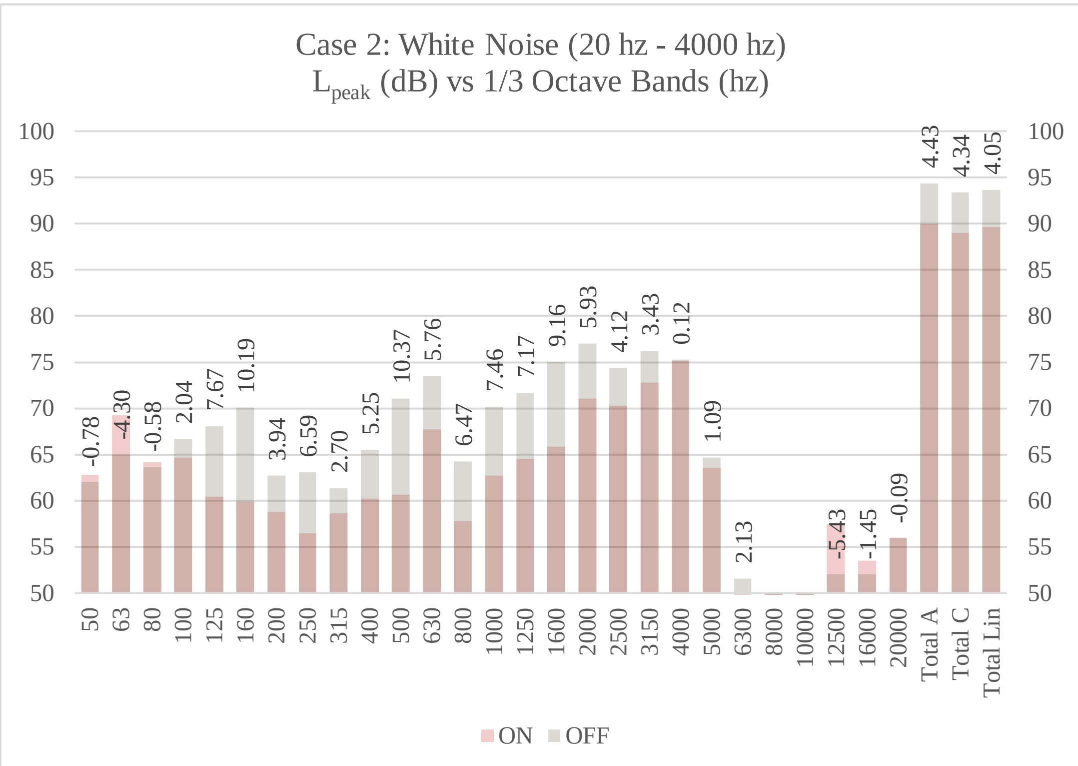

Figure 28: L_{peak} - 1/3 octave band noise measurement results for Case 2 - White Noise (20 hz-4000 hz).

At 160, 500 and 1600 hz 1/3 octave bands, up to 10 dB reductions are obtained. However, in low frequency bands, system did not perform as good as mid and high-mid frequency range. Reasons for this may be explained by acoustic feedback of the control signal to the reference microphone.

Although performance of the system at low frequency range is not as high as expected, reductions obtained in low-mid to mid frequency range prove that the proposed system is efficient as a standalone environmental noise barrier.

5.3. CASE 3: SINE SWEEP (100 hz - 1000 hz T_{sweep}=10 seconds.)

Results obtained in Case 1 and Case 2 shows that as system works with a sampling frequency of 8 khz, has an effective range up to 4 khz, for the pseudo random noise cases, best performance is observed between 125 hz and 3.15 khz 1/3 octave bands.

Last case resembles the use scenario of the proposed system against the unsteady noise sources, frequency and amplitude of which changes in time.

In order to simulate this behavior, monotonic sinusoidal sweep signal from 100 hz to 1000 hz is used. Response of the system to the mentioned disturbance reflect its adaptability to changing characteristics of a noise source such as traffic noise observed during acceleration or deceleration of vehicles. Moreover, robustness of the system against low frequency monotonic excitations is tested. At the end of the ten-second sweep cycle, frequency of the excitation signal instantaneously drops from 1000 hz to 100 hz, which is an extreme condition for an adaptive system.

Results of the measurements taken for noise generated with 100 hz - 1000 hz sine sweep are presented in Table 8, Figure 29 and Figure 30.

Table 8: Measurement Results of Case 3 - Sine Sweep (100 hz - 1000 hz T_{sweep}=10s).

Case 3: Sine Sweep (100 hz - 1000 hz, T_{sweep}=10s)							
				L_{peak}	L_{max}	L_{min}	L_{eq}
Profile 1	**A Weighted**	**Fast**	**OFF**	95.89	92.14	70.85	84.89
			ON	91.43	85.34	59.74	76.01
			DIFF	4.46	6.80	11.11	8.88
Profile 2	**C Weighted**	**Fast**	**OFF**	100.18	95.31	72.47	88.38
			ON	93.73	87.27	68.79	78.68
			DIFF	6.45	8.04	3.68	9.70
Profile 3	**Linear**	**Fast**	**OFF**	100.43	95.42	72.48	88.41
			ON	94.24	87.25	69.00	78.71
			DIFF	6.19	8.17	3.48	9.70

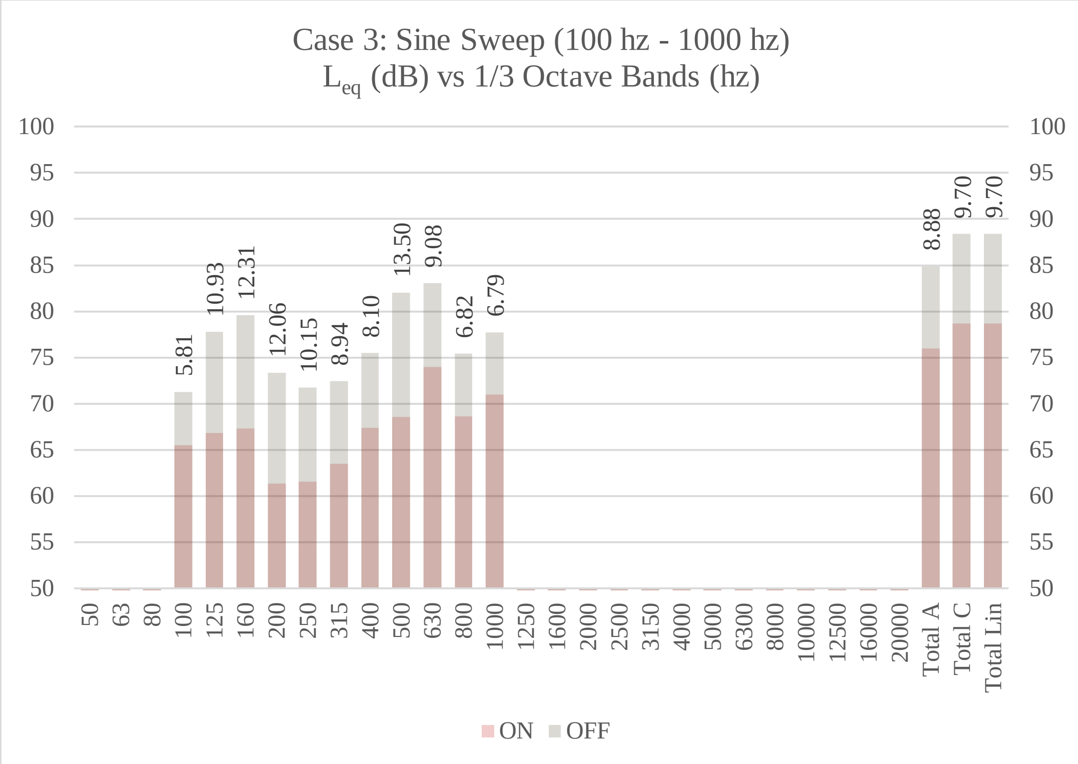

Figure 29: L_{eq} - 1/3 octave band noise measurement results for Case 3 - Sine Sweep (100 hz - 1000 hz T_{sweep}=10s)

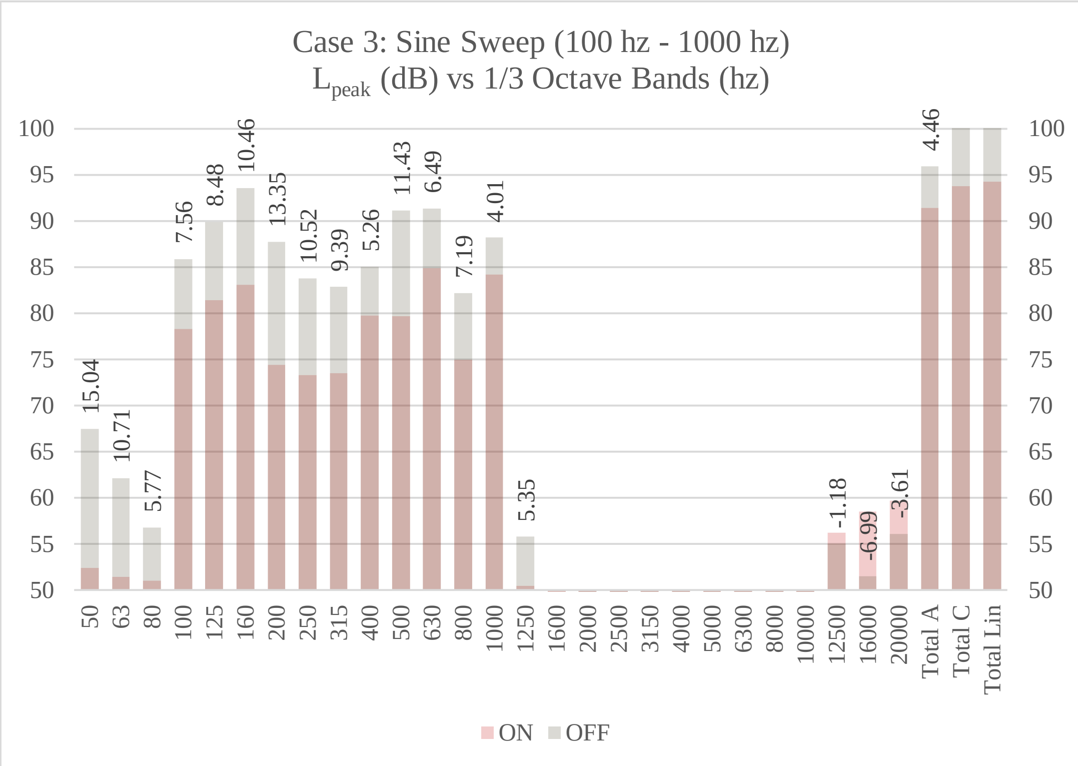

Figure 30: L_{peak} - 1/3 octave band noise measurement results for Case 3 - Sine Sweep (100 hz - 1000 hz) T_{sweep}=10s)

As can be seen in Table 8, approximately 9 dB reductions are obtained for measured L_{eq} values. Although reductions in L_{min}, L_{max} and L_{peak} values are not as high as the reductions in L_{eq}, they are the highest reductions obtained when all three cases are considered.

When the 1/3 octave band measurements are analyzed, a maximum 13.5 dB reduction is achieved in L_{eq}, which is at 500 hz 1/3 octave band. Also more than 10 dB reduction is achieved at 120, 160, 200, 250 and 630 hz 1/3 octave bands while a minimum of 5.5 dB reduction is achieved at 100 hz 1/3 octave band which is the lowest frequency component of the test signal. Similar to the first and second cases, maximum reduction is achieved at the low-mid frequency 1/3 octave bands.

Another interesting result of the third case is the reduction of peak values at lowest frequency range which shows that used FXLMS algorithm performed much better for monotonic noise. Also during the operation, at the end of each sweep cycle, where the frequency of the noise drastically changes from 100 hz to1000 hz, system preserved its stability.

When the results obtained from the third case are analyzed, proposed system is capable of achieving significant reductions in low-mid to mid frequency range while reserving its stability against rapid changes on the characteristics of the noise source.

Analysis of the results obtained from measurements of different cases show that, proposed ANC system, active noise barrier, is effective for reduction of traffic related environmental noise in open spaces. For some extreme cases reductions up to 14 dB in mid-frequency 1/3 octave bands are achieved. Moreover, a total reduction of 4 dB is achieved for the band limited white noise, which verifies the effectiveness of the system for the working frequency range.

CHAPTER 6

CONCLUSION

This thesis shows that proposed ANC system, as named in the thesis, active noise barrier, is a prominent control strategy for the reduction of the traffic related environmental noise as a lightweight, low cost, scalable and state-of-art alternative to conventional bulky and costly passive noise barriers.

The performance of the proposed system is investigated through case studies. The study shows that proposed system is able to decrease low-mid and mid frequency components of a broadband white noise signal up to 6 dB. In the study, up to 10 dB reduction was achieved for low-mid and mid frequency components of band limited white noise. In the case of sinusoidal sweep disturbance, reductions up to 14 dB were observed. As the results imply, ANC is a prominent approach for control of environmental noise.

Effective range of the system is found to be from 125 hz to 1600 hz under the mentioned test conditions, which corresponds to the most annoying frequency range of the traffic related environmental noise.

When the obtained results are compared with the studies present in the literature, noise reduction performance of the proposed prototype is similar to the systems with equivalent architecture and control strategy. Although it is not practical to compare the performance of ANC as a stand-alone system with passive noise barriers as passive noise barriers are means to control noise on the source while ANC is a mean to control noise on the receiver, measurement results show that ANC system is powerful enough for reducing the noise at receiver position.

Control action used for the realization of the prototype, feedforward FXLMS algorithm is one of the most common algorithm used for ANC. Although use of feedforward FXLMS is very common and algorithm itself is performing well for most of the application areas, there are much better and more complex alternatives which is proven to outperform the FXLMS algorithm. However, use of more complex alternatives require more computational power and for the cases where the noise can be modelled with measurable parameters obtained from the system, increased number of acoustic or non-acoustic sensors. Especially, alternatives which are more robust to non-linarites due to time variant characteristics of the acoustic paths and the characteristics of noise itself, can be employed for the control of environmental noise. Integration of more robust control algorithms to use of ANC system against environmental noise is crucial for a sustainable performance.

Ease of application makes ANC systems a powerful potential solution for the sites where construction of passive noise barriers is inadequate. Moreover, ANC applications does not require any preliminary preparation prior to installation as passive noise barriers requires. Scalable and lightweight characteristics of ANC systems promises portable implementations as well as arrays of systems may be cascaded in order to extend the effective range.

The advantages and the performance of ANC provide a new mean to control environmental noise as a standalone or being a part of insulation systems or sound barriers.

When the advantages of the ANC systems over passive noise barriers are set aside, only a few disadvantages appear. Most important disadvantage of ANC systems arises from its electronic based architecture. Ageing of the electronic and electro-acoustic components may result in decrease of the performance. Hence, ANC systems should be maintained regularly and worn of components should be replaced. However, its small scale, high performance and modular application possibilities makes ANC superior to passive noise barriers.

With the advances in technology, digital signal processing approaches and hardware, potentials of ANC will realize, resulting in better control performance while decreasing in scale and cost.

Most critical issue to be considered for the implementation of such a system should be stability. An unstable ANC system can cause increase in noise as the reproduced control signal becomes unstable. A control signal produced by an unstable control system becomes noise itself and adds up to the present noise resulting in overall increase. Hence, noise characteristics, available system components, control strategy to be applied and working frequency of the system should be carefully determined in order to ensure stable operation.

It is clear that proposed system, as a prototype, is not ready for direct implementation to the site. Most of the system elements are not weather and dustproof. Initial consideration for applications employing electro-acoustic means of controlling noise should be improved for outdoor conditions. As an example, IEC 60529 or an equivalent standard which describes a system for classifying the degrees of protection provided by enclosures of electrical equipment for two conditions: the protection of persons against access to hazardous parts and protection of equipment against the ingress of solid foreign objects and the ingress of water should be in consideration.

Also, in order to increase the competitiveness of ANC systems over conventional passive barriers, possibilities of new materials for transducers should be researched. New materials in speaker and microphone design will lead lighter systems with reduced energy needs.

In future, active noise barriers can be integrated with smart city systems, enabling the employment of noise specific algorithms for changing characteristics of the noise source within a day. Even system may be taken offline for the specific hours of a day when the environmental noise is below limiting values, in order to save energy.

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