Master of Science in Engineering

Construction Noise Management using ANC Technique on Sites

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Abstract

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Recently, many people have been seriously impacted by noise generated from construction sites. Accordingly, there have been increasing numbers of complaints and disputes. These complaints and disputes can cause delays and stops of project, resulting in the loss of time and money. For this reason, the Korean government is trying to improve the passive noise control system depending on soundproof walls. However, passive noise control is insufficient to reduce low-frequency noise, and only efficient for lowering high-frequency noise. Therefore, the purpose of this research is to suggest a noise management model using active noise control (ANC) as a new approach to supplement the limitations of passive noise control in construction sites.

The ANC management model consists of pre-planning, simulation, and implementation phases. ANC simulations have been conducted to examine its applicability for construction equipment and have progressed in the single-channel system based on the assumption of applying ANC to the closest location.

Based on the results of the experiment, it was confirmed that noise cancellation is highly efficient in low and mid-frequency bands of below 1000Hz, and its performance slows down as the frequency increases. In addition, the noise cancellation effects are high for equipment such as earth augers, vibration rollers, air compressors, dump trucks, and excavators. However, in the case of equipment that generates an impact sound, such as rock drills, jack hammer, and pump car, the noise cancellation effects are deficient compared to other equipment.

This research is expected to be an improved solution for attenuating the noise generated from construction sites. In addition, the ANC management model can be utilized as an alternative to passive noise control.

Keywords: Active noise control, ANC Simulation, Noise management model, Construction noise, Low frequency noise

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Chapter 1. Introduction

Recently, there has been an increasing awareness of environmental issues and the importance of the environment (Towers, 2001; Cheuk, 2000). This is because as the quality of life has been improved by the development of civilization and technology, the needs of people who want to live in a tranquil environment have also increased. Due to these changes in people's perceptions regarding environmental pollution, there is a growing tendency for disputes and complaints related to environmental issues to arise.

Particularly, in the case of construction work implemented in residential areas, many complaints have occurred due to the variety of noise sources generated from construction equipment and construction work and the increasing scale of construction. According to the statistics of the Environmental Dispute Committee (EDC, 2012), during the last 10years, disputes concerning noise accounted for 86 percent of the total complaints.

Table 1-1 Environmental Pollution in Korea (EDC, 2012)

Year	Total	Noise pollution	Air pollution	Water pollution	Right of light	Etc
Total (%)	2727 (100%)	2,336 (86%)	171 (6%)	77 (3%)	91 (3%)	52 (2%)
’12.6	126	102	9	2	9	4
’11	185	164	7	3	6	5
’10	174	148	3	6	10	7
’09	283	241	13	2	18	9
’08	209	173	8	3	22	3
’07	172	142	7	3	15	5
’06	165	150	8	3	1	3
’05	174	151	11	5	6	1
’04	223	206	8	3	4	2

Among them, disputes related to noise generated from construction sites accounted for 89.2 percent of the total complaints. Construction noise thus seriously affects the environment and human beings. Further, complaints related to construction noise increased from 19,666 cases in 2005 to 24,180 cases in 2009, a 23 percent increase.

In this way, complaints and disputes regarding the noise generated from construction sites lead to a negative image of corporations, delays and interruptions in the projects, and economic losses, and this trend of complaint and disputes has become significant and collective. Therefore, it is necessary to more effectively control construction noise (Ko et al., 2004).

1.1 Research Background and Objectives

Under this background, the government is trying to break from the noise policy depending on soundproof walls and establish a plan to strengthen the management of noise at the source through noise measures such as limitations on the use of construction equipment that emits loud noises, a survey on the mental and physical effects of noise on the human body, and the computation of reasonable damages (Ministry of Environment, 2010).

However, despite these efforts, the approach by passive noise control that depends on soundproof walls has a limitation to reduce mental stress and physical damage on human body (Elliott and Nelson, 1993; Guo and Pan, 2002c). In addition, the traditional noise control approach in construction sites where various noise sources exist in a complex manner is only effective for high-frequency noise, not low-frequency noise (De Salis et al., 2002; Kuo and Morgan, 1999). Therefore, a noise management method is required to deal with low-frequency as well as high-frequency noises.

In other industries, research on active noise control has been progressed as a new way to reduce noise. Active noise control is a noise control technique that aims to reduce the sound pressure level by canceling unwanted acoustic waves with electronically generated acoustic waves of equal amplitude but an opposite phase (Guo et al., 1997a; Snyder, 2000). This technique has been tried as a complement to passive noise control, which reduces the noise level by absorption and insulation (Kim, 1994). Nevertheless, the research on noise that is generated from construction sites using active noise control is inadequate.

Therefore, the purpose of research is to suggest a noise management model using active noise control technique to reduce noise generated from a construction site and to supplement the limitations of passive noise control.

For this purpose, simulations of active noise control are implemented. Subsequently, the noise levels of construction equipment before and after applying active noise control are compared. Based on the simulation results, the construction equipment and work type that can be applicable to active noise control are identified, and the applicability of the noise management model to construction sites is further examined.

1.2 Research Scope and Methodology

The present research targets the noise generated from construction equipment and construction work that has the possibility of causing complaints and disputes.

The research process is as follows.

(1) Case studies on the construction equipment and work type causing complaints and disputes are conducted through site-interviews and literature reviews.

(2) Based on the results of the case studies, improvement measures, the problems of traditional noise control, and the effect of low-frequency noise on the human body are investigated.

(3) Through literature reviews on active noise control, the current state of the ANC applications in other industries is investigated.

(4) Based on the study of active noise control, a theory is suggested applying active noise control to the construction industry.

(5) Furthermore, an ANC management model is established based on the theory which is suggested.

(6) Simulations of active noise control are performed. In addition, the noise levels of construction equipment are compared before and after applying active noise control.

(7) Through the simulation results, the applicable construction equipment and work type on construction sites are determined. As a result, the feasibility and applicability of the active noise control is validated

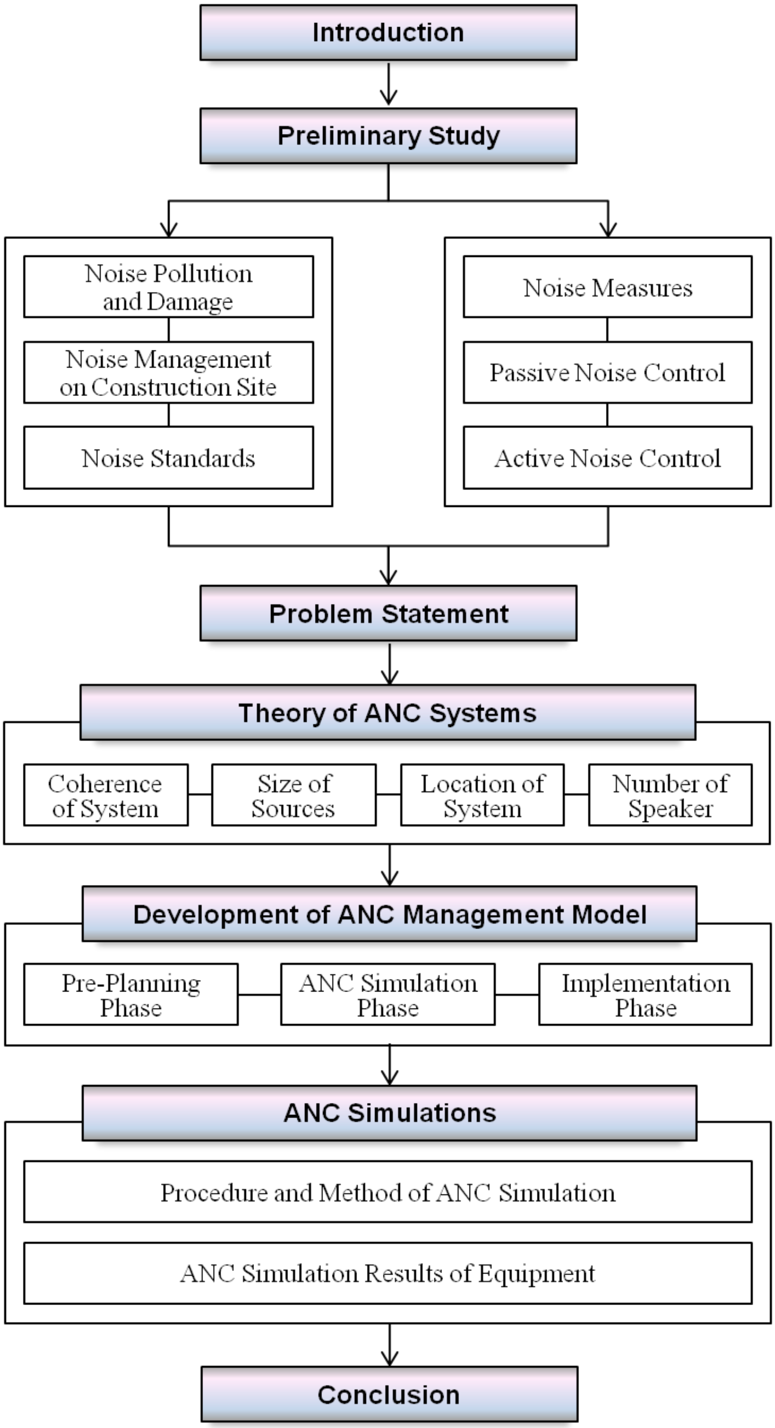


Figure 1-1 Research Process

Chapter 2. Preliminary Study

This chapter provides a clear understanding of the present conditions of noise damage, and noise management at construction sites and analyzes relevant literatures on passive noise control and active noise control. Further, the current state of noise regulations emerges from this chapter.

2.1 Noise Pollution and Damage

Among environmental pollution, noise pollution is the most susceptible type that causes people severe mental stress. By Cho and Kim (1997), a great deal of noise is generated in the earthwork, foundation, and destruction stages of the entire construction process. The construction equipment that generates much noise is in the sequence of pile drivers, rock drills, breakers. This equipment causes people much annoyance (Choi et al., 1996).

Table 2-1 Damage Type by Construction Noise (EDC, 2012)

Damage / Year	Mental	Building	Mental & Building	Livestock product	Acoustic Product	Farm product
2012. 6	23	5	31	21	1	10
2011	66	6	51	18	3	10
2010	63	6	33	22	8	13
2009	127	9	55	20	4	16
2008	71	4	57	19	5	18
2007	45	3	54	17	1	18
2006	74	3	40	20	2	6
2005	72	1	40	22	4	10
2004	107	1	49	33	1	9
2003	149	12	58	18	5	9
Total of 10 years(%)	797 cases (47.4%)	50 cases (3.0%)	468 cases (27.8%)	210 cases (12.5%)	34 cases (2.0%)	119 cases (7.1%)

According to the statistics of Environmental Dispute Committee (EDC, 2012) in Table 2-1, it was reported that mental damage accounts for 47percent, and mental damage and building damage accounts for 28percent of all damage caused by the construction noise. It has been the target of many complaints as noise generated from construction site causes physical damage as well as psychological damage, including stress and depressive disorder. Further, these complaints and disputes related to construction noise have occurred in metropolises where the population is distributed densely over a small area.

When examining the incidence rate of complaints on a regional basis as summarized in Table 2-2, approximately 49percent of total complaints are concentrated in Seoul and metropolitan areas (EDC, 2012).

Table 2-2 Incidence Rate of Noise Complaints (EDC, 2012)

Areas / Year	Seoul	Gyeonggi	Other areas	Sum
‘2012. 6	25	16	85	126
‘2011	52	26	107	185
‘2010	35	46	93	174
'2009	79	71	133	283
'2008	37	54	118	209
'2007	25	25	122	172
'2006	34	40	91	165
'2005	34	39	101	174
'2004	59	59	105	223
'2003	94	59	139	292
Total of 10 years(%)	474cases (24%)	435cases (22%)	1094cases (54%)	2003cases (100%)

This is because the scale of construction becomes larger than that of the past and the use of larger construction equipment that generates a level of high noise has increased according to the growth of high rise apartments and remodeling and renovation.

In the case of construction implemented in metropolitan residential areas, noise and vibration generated during construction projects have a harmful effect in the peripheral areas, as the distance between the adjacent buildings is narrow even if soundproof walls are installed. Therefore, it is necessary to ensure effective and systematic management for reducing construction noise. Fig. 2-1 presents the noise level of construction equipment, and it is confirmed that most of equipment have a high noise levels that exceed noise regulations.

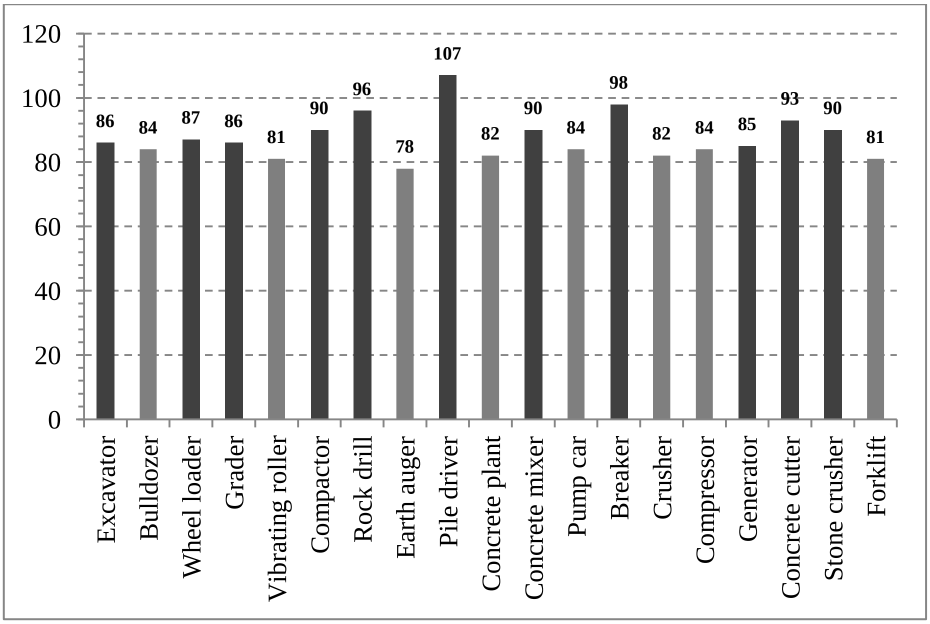


Fig. 2-1 Noise Level of Construction Equipment (National Institute of Environmental Research)

2.2 Noise Management on Construction Sites

Most of the construction companies develop their noise management plans through the discussions with residents of areas where noise damage may occurred, and select the appropriate construction method through preliminary surveys and basic noise assessments in the early stages (Fig. 2-2).

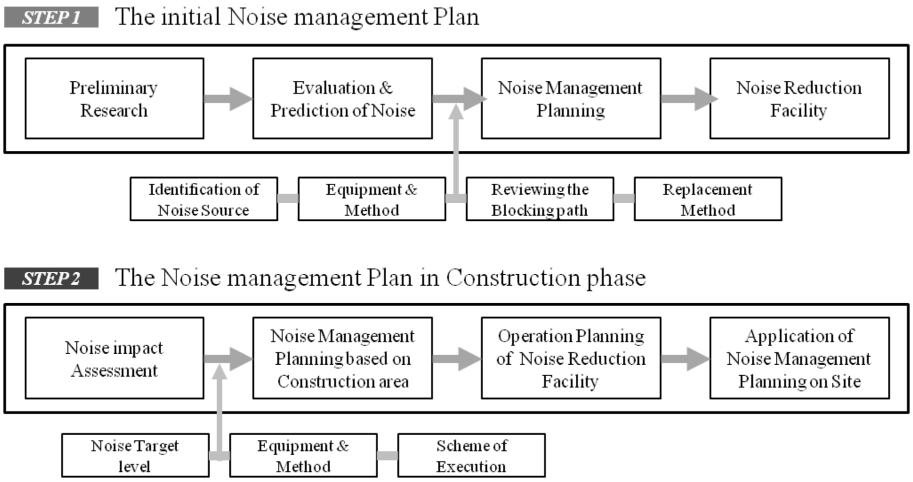


Fig. 2-2 Noise Management Process of Construction Company

However, these measures have a limitation to reduce disputes and noise damage. Because actually noise measures of construction company are mainly to install soundproof walls along the boundaries of construction sites.

According to the statistics of the Environmental Dispute Committee (EDC, 2012), construction companies reimburse a considerable amount of the total 11 billion owing to noise complaints on construction sites. Nevertheless, construction companies continually remain in conflict with people who file complaints, and the construction process has been delayed in response to it.

This is because the compensation rate for noise complaints is merely about 10%. Besides, if these cases in which the problem is solved through an agreement with residents without going through the dispute procedure are included, the damages paid by construction companies would increase significantly.

According to the results of on-site interviews, most companies have their own manual for noise management. However, when noise problems are occur, there are relatively few cases in which companies apply their manual to construction. This is because their manuals for noise management have no specific guidelines or plans. When complaints about construction noise have occurred, many companies have solved the problem via temporary measures. Because these inappropriate actions have continued until today, there are no fundamental measures for solving the noise problem.

2.3 Noise Regulations

Table 2-3 shows the recommended values of noise presented by the International Organization for Standardization (ISO).

ISO in 1971 established a noise criterion that takes into account individual differences to develop a noise standard. This criterion has been used as the basis for noise regulations in each country.

Table 2-3 ISO`s Noise Standard (ISO1996)

Target areas	Noise Level		
	Day	Evening	Night
Residential area Hospital, Care facilities	45dB	40dB	35dB
Suburban residential area Small road area	50dB	45dB	40dB
Urban residential area	55dB	50dB	45dB
Workplace and a mixed residential area with artery	60dB	55dB	50dB
Trade and Administrative district	65dB	60dB	55dB
Industrial area	70dB	65dB	60dB

Many countries have set up noise standards for construction sites as a political goal. Moreover, because individuals' perception of the same noise may differ, many countries have tried to apply noise regulations in a range that is appropriate for the situation of each country (ETRIK, 2006). In Table 2-4, the Swiss have prevented high noise levels from occurring over long periods of time by setting up noise criteria that should not be exceeded.

Table 2-4 Noise Control Standard in Swiss (ETRIK, 2006)

Target area	1month	1~6month	6month
Hospital area	70 dB(A)	65 dB(A)	60 dB(A)
Housing area and school area	75 dB(A)	70 dB(A)	65 dB(A)
Housing and industrial area	85 dB(A)	80 dB(A)	75 dB(A)
Traffic and Industrial area	90 dB(A)	85 dB(A)	80 dB(A)

Furthermore, Japan has applied noise regulations by subdividing construction equipment and construction work, and specifying working hours of the day and the maximum working period. Table 2-5 presents Japan's noise regulations.

Table 2-5 Noise Control Standard in Japan (Yang, 2009)

The type of work	Standard	Working hours		Maximum work period	
	dB(A)	A	B	A	B
Pilling & Wrench work, Work using excavator such as concrete breaker, bulldozer, power shovel	75			1day 10time	1day 14time
Work using a machine to harden the ground	70	06-21	06-22	Consecutive 1month	Consecutive 2months
Work carrying concrete	75				
Work with power tools, Concrete finishing	80	07-19	06-22	1day 10time consecutive 6days	1day 14time consecutive 6days
Demolition of buildings, Destruction work that uses a steel ball or gunpowder	85				

Meanwhile, the noise standard of construction site in Korea complies with life noise control standards (Table 2-6).

Table 2-6 Living Noise Control Standard in Korea

Target area	Source	Dawn	Day	Night
Residential area, green area Settlement area, exercise and recreation area, natural conservation area of quasi-city area School area, hospital, public library in the other areas	Noise generated from site	below 60dB	below 65dB	below 50dB
Other areas		below 70dB	below 75dB	below 55dB

When a construction project over a certain scale is performed by using equipment that emits a loud noise, it is required to report to the authorities in advance (Kim, 2001).

Domestic noise regulations have been applied consistently without establishing regional differences. Thus, it is difficult to apply noise regulations to a variety of situations related to noise problems, and cannot fully account for people’s subjective experiences and varying levels of acceptable noise (Park, 2006). In addition, domestic noise regulations make a noise assessment focused on high-frequency bands by depending on only decibel values.

Consequently, there are many cases in which the measured noise level is lower than the expected noise level when people are under stress. This result is because the influence of audible noise is only measured, and the influence of sound that cannot easily be heard, like low-frequency noise, is ignored (Kim, 2002). Therefore, substantial noise regulations and noise management that can reflect reality are required for reducing the damage caused by low-frequency and high-frequency noise.

2.4 Summary

This chapter consists of contents on the noise damage and noise management, noise regulation. Noise pollution of the environmental pollutions is a critical problem and causes severe mental and physical damage such as stress and depression. For this reasons, many complaints and disputes are engendered.

Nevertheless, noise measures on constructions site have a limited ability to reduce disputes and complaints. This is because noise measures are mostly to set up soundproof walls along the border of construction sites. In addition, domestic noise regulations have concentrated on high-frequency noise depending on only decibel values. Consequently, the influence of noise that cannot easily be heard such as low-frequency noise is ignored and damage caused by low-frequency noise has been increasing.

Therefore, substantial noise management on sites and noise regulation standards are required to diminish the damage caused by the low-frequency and high-frequency noise.

Chapter 3. Noise Control and Management

The noise measures to minimize the effect on the noise generated from construction site are categorized as source control, path control, receptor control (Gilchrist et al., 2003; Schexnayder and Ernzen, 1999).

3.1 Noise Measures

(1) Source control is used to manage a noise where it occurs. This is a method using construction equipment generating a low noise level or avoiding the use of equipment generating a high noise level at the same time by adjusting schedule of equipment, and adhering to a flexible material to the impact point (Gilchrist. A, 2000).

(2) Path control is a method of installing soundproof walls at the propagation path where a noise spreads. This is used to install facilities such as soundproof walls, acoustic absorbents, and to attenuate noise by increasing the distance between noise sources and receiving points.

(3) Receptor control is the most difficult and expensive method of the noise measures. This method is used to reduce noise by wearing a device for hearing protection or installing acoustical facilities

Of the above three measures, source control is the most effective measure of eliminating construction noise and is the easiest way to manage the noise at a construction site (Webb,1976).

However, it is difficult to apply changes of construction schedule to the actual construction process, due to limitations related to the construction period and cost. For this reason, the noise measure of attenuating noise by blocking the propagation path is mainly used on construction sites.

Nevertheless, it is difficult to obtain a sufficient reduction effect in the case of using soundproofs to reduce noise, since construction noise has a lot of energy at a low frequency band, and it spreads out over the soundproof walls by the diffraction phenomenon (Lee, 2007).

Table 3-1 shows the preliminary study of noise measures. Most of the study involves formal research, such as measuring the noise of construction equipment, suggesting general management measures, and identifying the frequency response of the equipment. Besides, because much of the research is carried out by placing emphasis on the passive noise control, there are many limitations in solving the noise problems.

Table 3-1 Preliminary Study of Noise Measures

Field	Author	The contents of study
Noise measures	Koo etal 2 (2009)	Investigation on limitations and cases of noise measure on construction site
	Oh etal 2 (2009)	The development of noise prediction program for calculating the height and the position of sound proof wall
	Ko etal 3 (2004)	Deriving the main issues at the stage of preliminary and detailed design
	A. Gilchrist etal 2 (2003)	The development of the system for optimizing the location of noise barrier
	Thalheimer, E. S. (2000)	The proposal of noise management plan at source, path, receptor point
	Kim etal 5 (1998)	The analysis on the characteristics of attenuation and propagation of noise

3.2 Passive Noise Control

Noise control is generally divided into passive noise control and active noise control. Passive noise control is a method that is mainly used on construction sites; it means noise measures such as placing soundproof walls or installing acoustic facilities at the receptor point after noise is produced.

Generally, soundproof walls are considered as a representative of passive noise control. Soundproof walls are mostly used to minimize the harmful effects of noise on construction sites (Thalheimer, 2000). According to Koo et al. (2009), a fixed soundproof wall is a general measure to prevent construction noise, and actually soundproof facilities are used in the sequence of soundproof walls, soundproof curtains, and silencers in controlling construction noise.

In the case of construction implemented in residential areas of metropolises, noise management that adds temporary soundproof walls to fixed soundproof walls is mainly performed to minimize noise damage.

Nonetheless, noise management using soundproof walls is deficient to forestall noise from spreading by diffraction (Wang and Guo, 2013). Furthermore, high-frequency noise is easy to reduce with soundproof walls, but low-frequency noise has a long wavelength and is not easily attenuated (Shiro et al., 1991).

Therefore, the width and the height of soundproof walls should be large enough to reduce both low-frequency and high-frequency noise. As such, soundproof walls are not suitable to attenuate the noise generated from construction sites considering cost and performance.

Table 3-2 Noise Reduction effect and Cost (Koo, 2009)

Technology	The effect	Cost(1000 won)
Air soundproof wall	5dB	13000/piece
Bucket crane soundproof wall	5dB	8600/piece
Portable soundproof wall	8dB	3470/piece
Portable air mattress	8dB	3,000/set
Transparent soundproof panel	9dB	81500/set
Portable soundproof tent	10dB	71400/set
Magic panel	13dB	35/m²
Absorbing material plus Portable soundproof panel	15dB	600/piece
Soundproof wall of gang form	15dB	1160/piece
Split soundproof box	25dB	3475/piece

3.3 Low Frequency Noise

Low frequency noise usually refers to noise in the frequency range of 20~250Hz.

Because low-frequency noise is not easily audible, people are not often annoyed by such low-frequency noise. However, it causes mental stress such as depression and physiological disorders similarly to high-frequency noise. Furthermore, low-frequency noise is a critical problem because it can cause secondary damage by vibrating doors or windows.

For this reason, developed countries have come to recognize the need for research and management of low-frequency noise; as such, studies have recently been done on the health effects of low-frequency noise (Ministry of Environment, 2009). Table 3-3 indicates the health effects of low-frequency noise on the human body.

Table 3-3 Health Effect of Low Frequency Noise (Chung, 2012)

Organs	The health effect
Circulatory system	· Increase and decrease of heart rate · Decrease of systolic blood pressure
Respiratory system	· Increase and decrease of respiratory rate
Nervous system	· Increase of α, β, θ brain wave in amplitude · Decrease α-wave amplitude in threshold level
Endocrine system	· Increase of adrenaline, dopamine(2-20Hz, 90min)
Sleeping	· The depth of low sleeping · The occurrence of arousal response
Others	· Increase in the number of eye blinkering · Vibration and loss in the eyes

European countries put in place guidelines for low-frequency noise in the 1990s, and Japan arranged guidance in 2004. Further, the Taiwanese government legislated a legal enforcement act on low-frequency noise at the end of 2008, and it has been applied (Jung, 2012).

Many studies related to noise in Korea have focused on reducing mid and high-frequency noise, and the desired results have been achieved. However, according to the reduction of mid and high-frequency noise, a phenomenon has taken place in which low-frequency noise is heard loudly and clearly. As a result, low-frequency noise is causing symptoms such as dizziness and suffocation (Jung, 2012).

Kim (2002) experimentally confirmed the fact that as the frequency becomes lower in the frequency range between 1Hz and 1000Hz, it increases the level of stress experienced by individuals. In other words, the lower frequency decreases below 1000Hz, the greater its impact on the human body. Thus, enhanced noise measures are required for managing low-frequency as well as high- frequency noise.

3.4 Concept of Active Noise Control

Recently, developed countries have progressed on the study of active noise control by recognizing the limitations of passive noise control. The active noise control is a technology for canceling noise by emitting a sound with the same amplitude and reversed phase. This concept was designed by Paul Lueg of America in the 1930s (Kuo and Morgan, 1999; Snyder, 2000).

However, active noise control has been difficult to apply to actual noise problems because of the technical reasons in the early stages. Despite these limitations, practical applications were advanced rapidly in the 1980s with the development of the electronics industry and digital signal processing technology. In developed countries including the United States and Germany, Japan, active noise control technology has been applied to electronic devices such as earphones, aircraft, trains, and automobiles (Kim, 1994). Table 3-4 shows the preliminary study of active noise control

Table 3-4 Preliminary Study of Active Noise Control

Field	Author	The contents of study
Active Noise Control	Ryo et al. (2011)	Performance comparison based on the number of speakers and noise sources, the position of the control source
	J. Guo and Pan (2002)	Analysis of applicability and effect of active noise control depending on the placement of system, moving source
	Nam and Lee (2004)	Study on the determining the optimum position of microphones and control speakers in active noise control
	Baek (2004)	Research on the optimum position of control source and the comparison of the performance
	Snyder, S. D. (2000)	Theoretical study on the principle and application of active noise control
	Omoto. A and Fujiwara (1993)	Research on the position of the control source and deployment of the system to reduce the diffusion

A number of studies on active noise control have been conducted as a complement of passive noise control, but they are difficult to apply to construction sites, and the research on applications for duct and soundproof walls and windows has been recently progressed in the field of construction (Han et al., 2010). Nevertheless, the research on noise measurement and management plans to cancel noise by applying active noise control to construction sites is extremely deficient.

This is because the noise generated on construction sites, unlike the noise generated by other industries, has characteristics that are temporary and irregular, and construction work is performed in open spaces. For these reasons, there are restrictions in applying active noise control to construction sites.

On the other hand, active noise control has been applied to other industries since it is superior at attenuating for low-frequency noise, unlike passive noise control. Fig 3-1 presents the principle of active noise control.

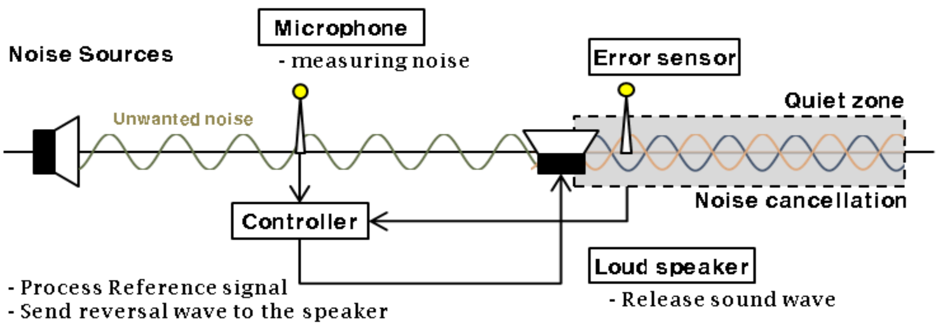


Fig. 3-1 Principle of Active Noise Control

The system of ANC consists of the following four components (Hansen, 2002; Silentium, 2008; Snyder, 2000).

(1) Reference microphone: The reference microphone records noise, and transmits the measured noise signal to the controller.

(2) Control system: This system generates a signal with the opposite phase and the same amplitude by processing the noise signal sent from the error sensors and microphones, and transmits the signal to the control speaker.

(3) Loud speaker: It serves to generate a sound wave to cancel construction noise in response to the signal processed by the controller.

(4) Error sensor: This sensor evaluates whether the noise was cancelled effectively. If the noise is not cancelled sufficiently, the error sensor transmits the measured error signal to the controller, and the signal is modified to improve the cancellation effect in the controller. Theoretically, the quiet zone is created behind the error sensor, and the noise level at this moment is zero (Guo et al., 1997a).

The deployment of the system's components in noise management using active noise control has a significant effect on the performance (Guo and Pan, 1999b; Snyder, 2000). In other words, the system must be arranged so that signals are coherently transferred on the basis of a smooth exchange of information in each system. Therefore, it is important to determine the most appropriate placement to maximize the effectiveness of the noise cancellation by adjusting the deployment of the noise source, the microphone, the control speaker, and the error sensor (Guo and Pan, 2002c).

3.5 Theory of Active Noise Control

(1) Coherence between the noise source and the signal emitted from the control speaker:

In order to effectively reduce construction noise, the noise source and the control source emitted from the speaker must be consistent (Snyder, 2000). If the noise source and control source are not consistent, the sound pressure level of the noise could be increased by constructive interference.

(2) Size of the noise source and control source:

The sizes of the control source and noise source should be balanced to reduce the noise generated from the construction site using ANC (Snyder, 2000). If the noise source is smaller than control source, it only has the effect of cancelling noise in certain areas, and it will have a limited ability to reduce the sound pressure in a wide area. In contrast, if the size of the control source is too large compared to the noise source, there is a risk of constructive interference occurring in other areas.

(3) Location of control source:

The wave generated by the pressure changes in the atmosphere spreads in the shape of a sphere from the source. Therefore, it is effective to arrange the system so as to minimizing the distance between the noise source and the control source by installing the control source in a location close to the noise source to reduce the surface area of the noise emitted (Guo and Pan, 1999b; Hansen, 2002; Snyder, 2000).

(4) Number of control speaker:

As the number of control speakers is increased, the ANC system's noise cancellation performance is generally improved. However, even if the number of speakers is increased, the noise cancellation effect is reduced at some point (Nam and Lee, 2004). Namely, it is necessary to decide the optimal number of speakers considering the system's performance and the cost. This is because there is a limitation of system performance to attenuate the noise.

(5) Arrangement of active noise control system:

Cancelling noise using active noise control is to create a quiet zone (Guo et al., 1997a). The arrangement of the system, including the noise source, the control source, and the error sensor, should be within a certain range to make a quiet zone (Hansen, 2002; Snyder, 2000). This is equally applied to the case of a moving source or an open space such as construction site.

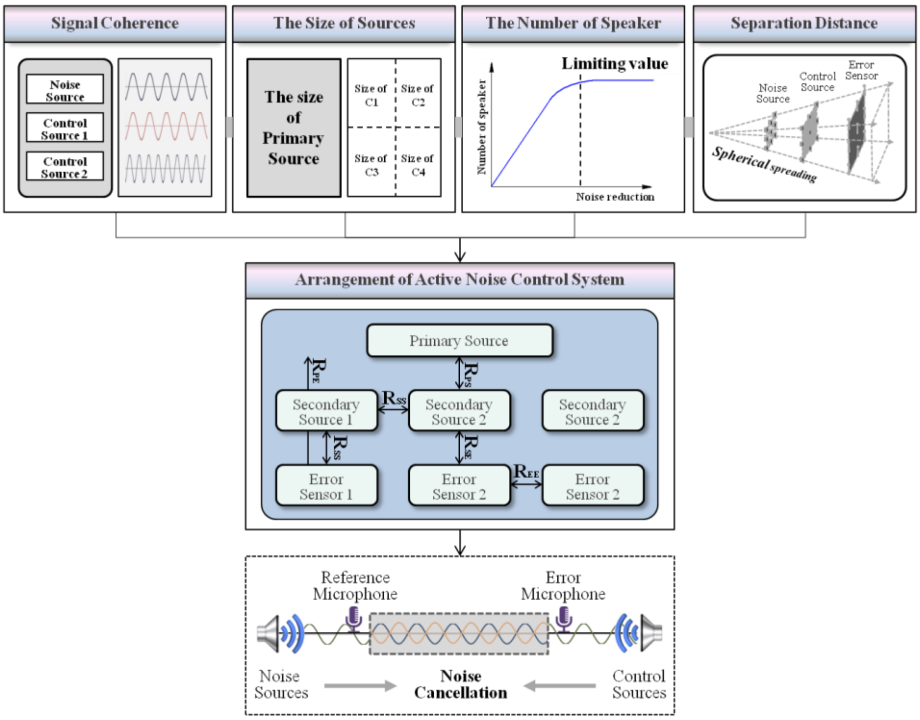


Fig. 3-2 Theory of Active Noise Control

3.6 Summary

The noise measures to minimize the noise effect on construction sites are classified into three methods: source control, path control, and receptor control. Of the above three measures, source control is the most effective method for lessening noise and is the easiest to manage construction noise.

In this chapter, the limitations of passive noise control and the effects of low-frequency noise on health are stated. Because construction noise made from equipment has a lot of low-frequency energy, it is difficult to attain a sufficient noise reduction by passive noise control. Thus, improved noise control is required to reduce low-frequency noise.

For this reason, the principle of active noise control is introduced as a complementary method to address the limitations of passive noise control, and the theory of active noise control is extracted based on a review of relevant literatures. The extracted theory is used as a basis to develop an ANC management model on construction sites.

Chapter 4. Development of Active Noise Control Management Model

A basic framework of ANC management model is based on the noise management plans used in construction companies, literature reviews on noise control, and on-site interviews. In addition, theory and strategies are added to the framework for application of active noise control to construction sites, and ANC management model is examined and improved by expert's opinion.

If ANC systems are properly arranged and applied to construction sites according to the suggested process of management model, a satisfactory noise cancellation effect can be expected. Fig 4-1 presents development procedures of ANC management model.

Fig. 4-1 Framework of Management Model Development

4.1 ANC Management Model on Construction Site

The ANC management model consists of pre-planning, simulation, and implementation phases. The specific contents of the noise management model applying active noise control to construction sites are as follows.

4.1.1 Pre-Planning Phase

(1) Understanding of the acoustical environment and the noise characteristics of construction equipment:

First, it is necessary to confirm the noise level and frequency response of the construction equipment and background noise, as well as information on areas that has a possibility to cause a lot of noise damage.

(2) Data acquisition on operational plan of equipment:

It is necessary to obtain information on the operational schedule and the number and location of equipment to be used from the drawing or process planning. These data must comply with the actual construction schedule as a basic data for the noise prediction.

(3) Noise prediction and assessment:

Based on the data gathered in the prior phase, the noise level that will be generated from the construction site is calculated. Information on the areas with the potential to cause a lot of damage using the calculated noise level is identified. These areas are specified as target areas to be intensively managed during the construction process. Further, data on the target area should be updated continually and applied to the construction process.

(4) Priority derivation for noise management:

Even if construction work is implemented after sufficient planning, it is possible for unexpected problems to arise. This is because construction involves risk and uncertainty. Therefore, noise management priorities should be derived by considering factors such as construction equipment, expected damage areas, and working time of the equipment.

(5) Establishment of management plan and alternative review:

It is essential to come up with noise measures through a multilateral review by considering the source control, path control, and receptor control instead of depending on only one measure. In addition, the overall noise management plan should take into account cost and feasibility.

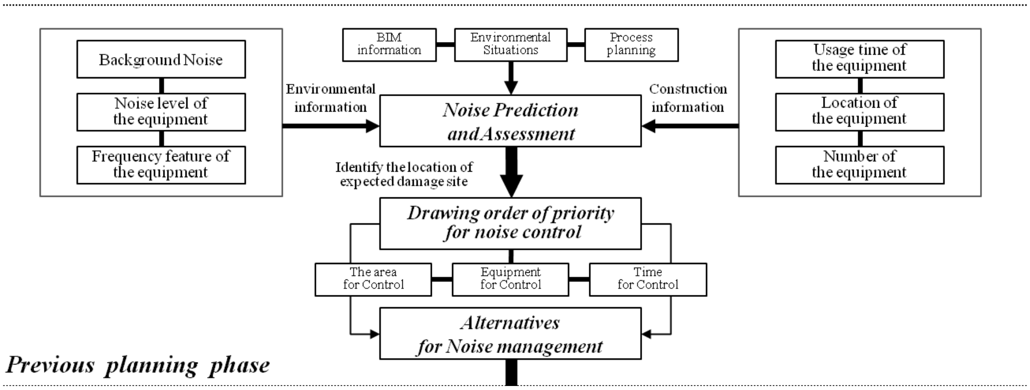


Fig. 4-2 ANC Management Model of Pre-Planning Phase

4.1.2 Simulation Phase

(1) Implementation of ANC simulation:

First, ANC simulation is performed after ensuring the consistency of the signals between the reference microphone, error microphones, and control source by adjusting the system’s arrangement. Based on the results of the simulation, check how much construction noise coming from the equipment is to be canceled.

(2) ANC calibration process:

ANC calibration is conducted to ensure the consistency of signals and to maximize the effect of noise cancellation. The actual measurements following the application of active noise control are compared with the optimal value of simulations. At this time, the ANC simulation is continuously performed until the optimal values and the actual measurements are as similar as possible.

(3) Result reviews of ANC simulation:

The ANC simulation is operated repeatedly to meet the noise regulations or targeted level by changing the deployment of systems such as the location of the control and the number of speakers, and the most effective arrangement is determined. At this moment, it is important to make the environment closely approximate the actual construction site.

(4) Preparation for application on construction sites:

If the noise cancellation is effective, active noise control can be applied to actual construction sites. However, the effect of active noise control may be deficient on actual construction sites, as they differ from the simulation environment. In this situation, ANC simulations are conducted repeatedly by reconstructing factors such as background noise and the working environment that are similar to the actual environment.

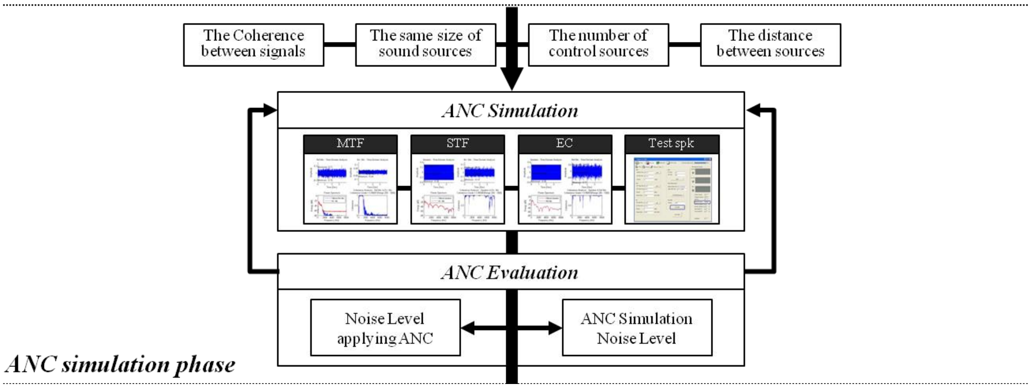


Fig. 4-3 ANC Management Model of Simulation Phase

4.1.3 Implementation Phase

(1) Identification of a control target:

The placement of the system and the method of active noise control can differ depending on whether the noise source is a moving source or a fixed source. In the case of a fixed noise source, it has a possibility to perform active noise control in diverse positions, including the noise source, propagation path, and receptor point. However, in the case of a noise source that moves continuously, such as dump truck, there are limitations compared to a fixed noise source in applying active noise control. This is because the system should be installed directly at the noise source or placed along the moving path. Therefore, it is important to identify the control target for effectively cancelling the noise generated from a construction site.

(2) Determination of control location and scope:

After identifying the target for noise control, the appropriate location for implementing active noise control is determined, including the noise source, propagation path, and receiver point. In addition, a suitable method for active noise control is determined after setting up the range to control the construction noise.

(3) Selection of active noise control method:

Global control is a method used to reduce noise throughout a wide area. In contrast, local control is used to cancel the noise in specific area. However, the local approach has a limited cancellation effect, as it has the effect of only cancelling noise in a partial area. Further, the global approach also has a constraint, in that the distance between noise source and control source should be very close. Thus, it is desirable to determine an appropriate control method by comprehensively considering factors such as the site condition, control target, surrounding environment, and zoning the construction site.

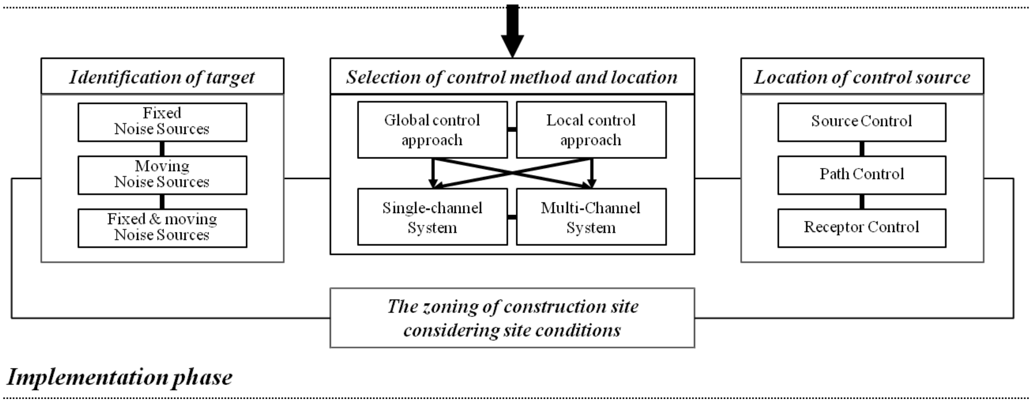


Fig. 4-4 ANC Management Model of Implementation Phase

Fig 4-5 shows the approach of Active Noise Control. As above mentioned, two approaches have constraints to cancel noise generated from construction equipment. For these reasons, a complementary approach is suggested to enhance noise cancellation effect. This strategy, which attenuates noise by zoning construction sites, can decrease number of control speakers and prevent noise level from increasing by constructive interference.

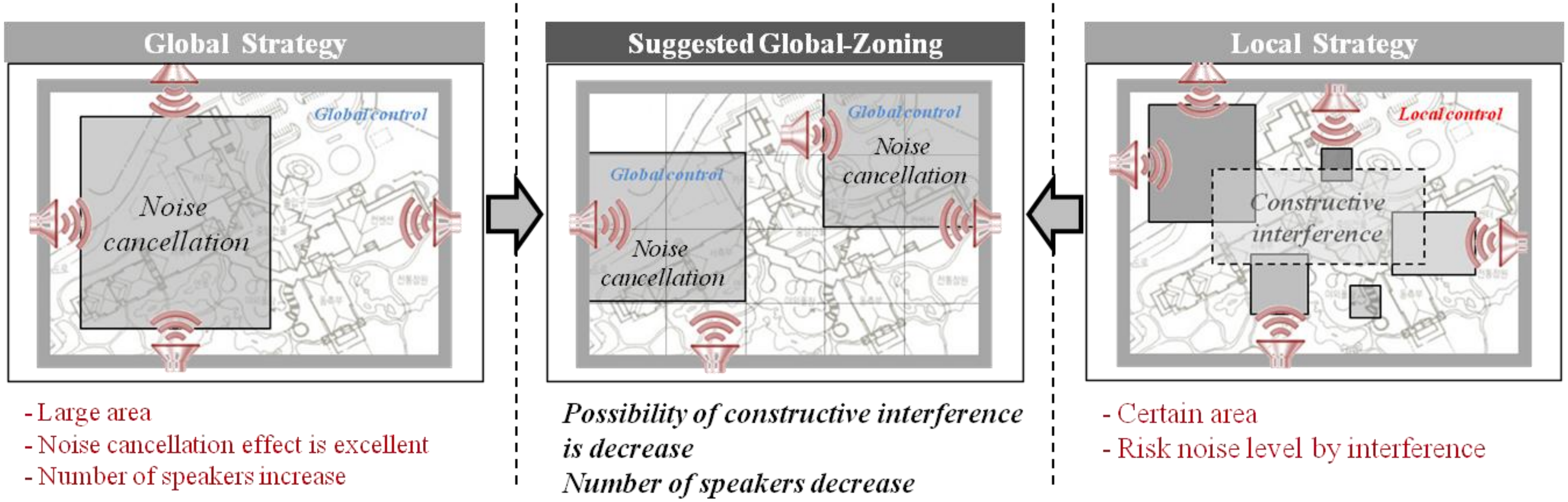


Fig. 4-5 Active Noise Control Approaches

The noise management model using active noise control on construction site is as follows.

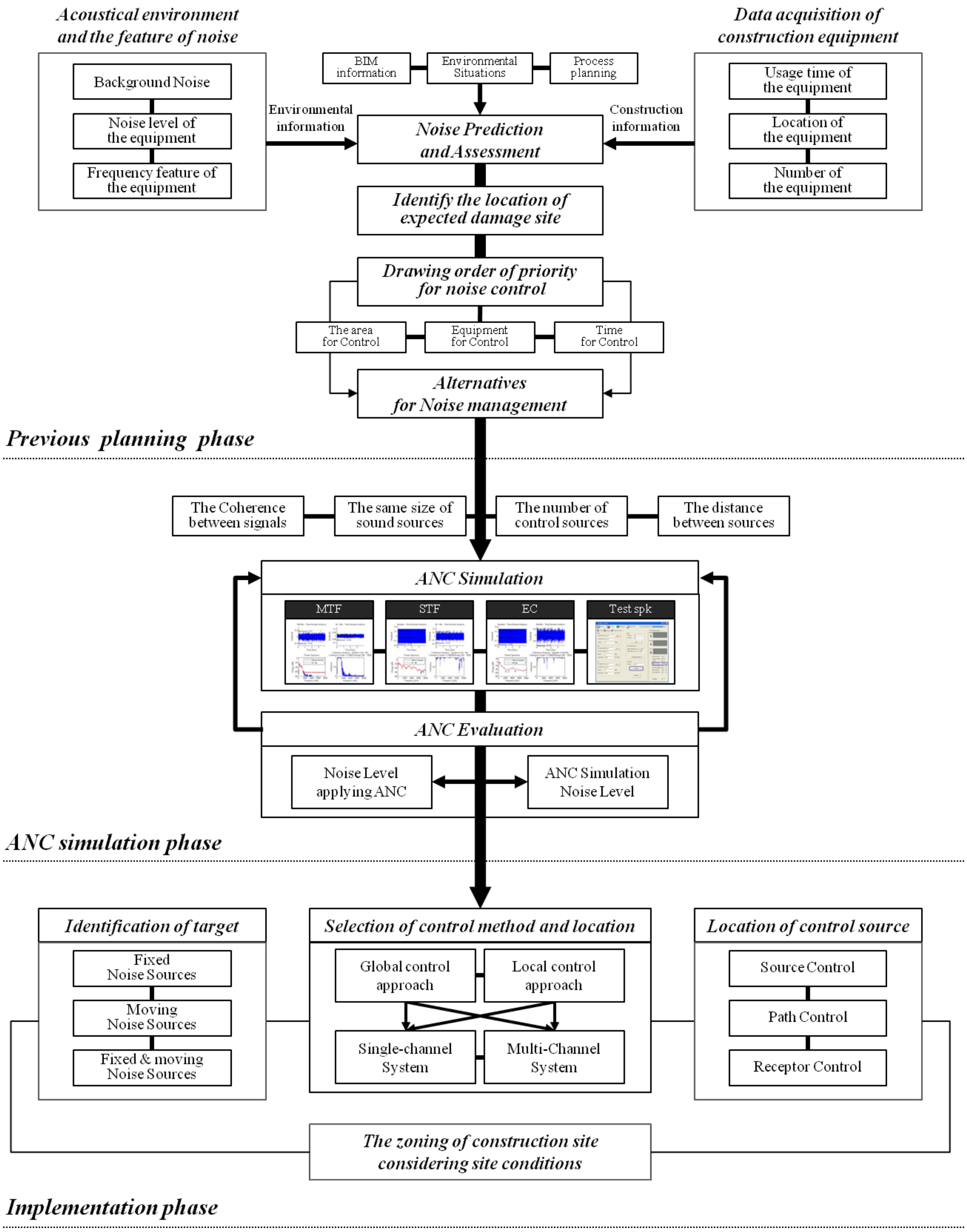


Fig. 4-6 ANC Management Model on Construction Site

4.2 Procedure and Methods of the Experiment

The simulation analysis was carried out to examine the feasibility of active noise control on construction sites and specifically to determine which work type or equipment is suitable for applying active noise control.

The active noise control experiment was conducted using Silentium's S-cube development, S-fan90 duct, noise measuring apparatus (TES1350A), 1 speaker, 1 laptop.

Fig. 4-7 Noise Measurement of Equipment applying ANC

This experiment was implemented in the single channel system based on the assumption of applying active noise control to the closest location where construction noise occurs to prevent noise from diffusing and to maximize the performance of active noise control. This is because source control is the most effective measure of eliminating construction noise by controlling the noise emission in all directions (Gilchrist et al., 2003; Thalheimer, 2000). The procedures of the experiment are as follows.

(1) The noise level of equipment: The original noise level of the construction equipment was measured.

(2) Microphone transfer function analysis (MTF): This is a process of evaluating and adjusting the transfer function of the error microphone and the reference microphone.

(3) Speaker transfer function analysis (STF): This is a process of evaluating and adjusting the transfer function of the speaker and the error microphone.

(4) Echo canceller analysis (EC): This is a process of evaluating and adjusting the transfer function of the speaker and the reference microphone.

(5) Test speaker: This is a process of testing the speaker limits in the low-frequency range by outputting different sine signals and measuring the reference microphone.

(6) ANC simulation: This is a process of identifying how much noise is attenuated by implementing a simulation based on the prior ANC calibration process. In addition, noise signal is converted into sound with the same amplitude and reversed phase.

(7) Gain adjustment: This is a process for adjusting parts that the effect of noise cancelling is declined and constructive interference occurs. This process should be repeated until the desired effect of noise cancelling is displayed.

(8) The noise level of equipment applying ANC: This is a process of measuring noise level of equipment that is emitted from S-fan90 duct through ANC simulation.

(9) Evaluation and analysis: This a process of identifying and analyzing noise cancellation effect by comparing ANC simulation results with actual measurement values.

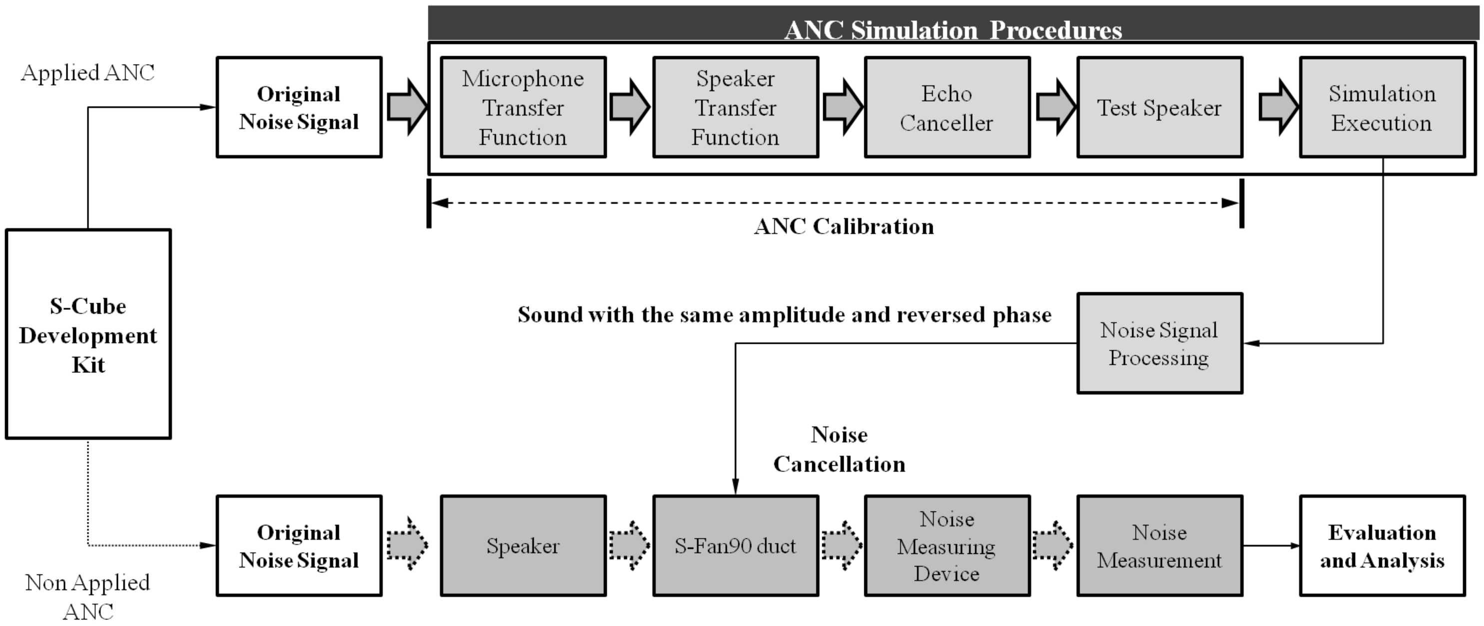


Fig. 4-8 Procedures of ANC Simulation

The ability to transmit noise signals accurately plays an important role for noise cancellation in the ANC simulation.

Therefore, if each system cannot transmit a consistent signal, the performance of the active noise control is reduced, or the noise level may be increased by constructive interference.

For this reason, the ANC calibration process should be conducted. This process aims to maintain the consistency of signals transferred among the speaker, error sensor, and reference microphone. At this moment, the coherence grade that indicates the consistency between the systems should be at least 9.2. Thus, the ANC calibration procedure is repeatedly carried out so that the coherence value is 9.2 or more at each stage of MTF, STF, and EC analysis. Like other construction equipment, the experiment of active noise control was accomplished through simulation procedures, such as those illustrated in Fig 4-9.

Fig 4-9 indicates MTF, STF, and EC analysis.

ANC simulation was performed after getting results which the connection of system such as speakers, error microphone, and reference microphone is stable.

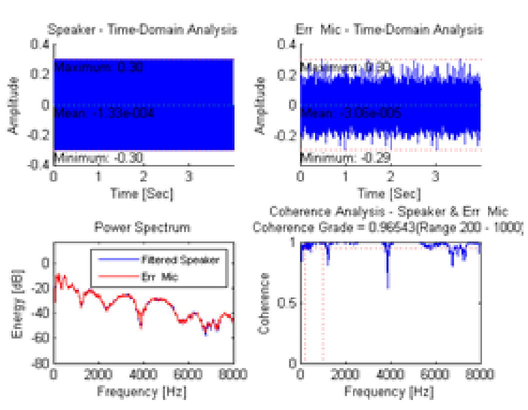
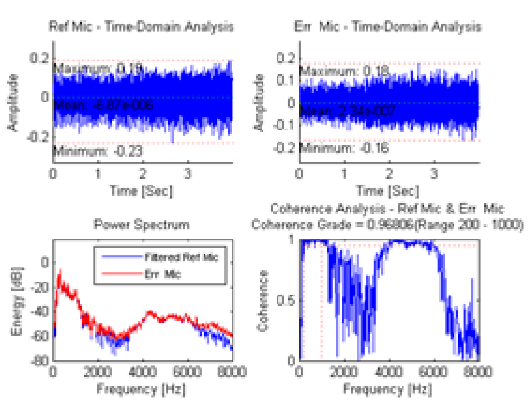
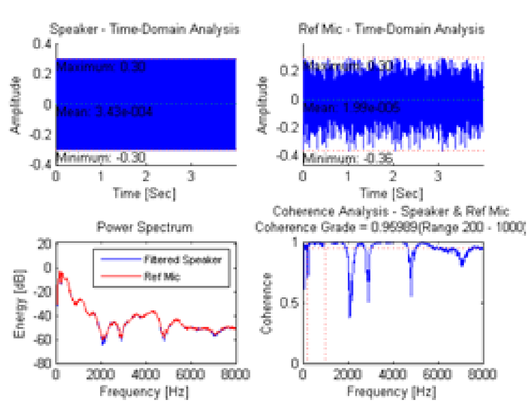
STF analysis	MTF analysis	EC analysis
		

Fig. 4-9 MTF, STF, and EC analysis

4.3 ANC Simulation Results

Based on the results of the experiment, it was confirmed that noise cancellation is highly efficient in the low and mid-frequency bands of below 1000Hz. However, the noise cancellation performance decreased as frequency increased, and there was barely a noise cancellation effect at high-frequency bands above 8000Hz.

Further, the difference between the optimal value of the computer simulation and the actual measurement value of the experiment was analyzed to be from 0.4dB to 10.5dB. This is because the value of the ANC simulation is the optimal value derived by considering the relationship between the noise of construction equipment and the opposite noise, excluding factors such as surroundings, background noise, and site conditions in the case of computer simulation.

Generally, if the ANC actual measurements reach 70-80% of the ANC simulation values, it explains that the noise cancellation effect of active noise control is appropriate.

The noise cancellation effect of construction equipment is as follows (Table 4-1). Most of the construction equipment has an excellent noise cancellation effect, and the simulation results have a noise cancellation effect of 8.7dB~13.7dB. This is a similar value to soundproof walls, having a noise reduction effect of about 10dB on average. In particular, it was confirmed that the application of active noise control significantly reduces the noise of equipment such as earth augers, vibration rollers, air compressors, dump trucks, and excavators, as construction equipment has a lot of low-frequency energy.

Fig. 4-10 shows the ANC simulation results of earth auger. Like other construction equipment, it was confirmed that noise cancellation was effective in the frequency b7and of below 1000Hz, and as the frequency increased, the noise reduction performance declined. Furthermore, though the optimal value of noise reduction by ANC simulation was 12.19dB, the actual effect of noise cancellation fell short of its optimal value.

When active noise control was applied to earth auger, the sound pressure level of 68dB~71.6dB was measured, and simulation result shows that noise level of 8dB~10dB was reduced compared to the sound pressure level of 78dB~79.4dB which active noise control is unapplied.

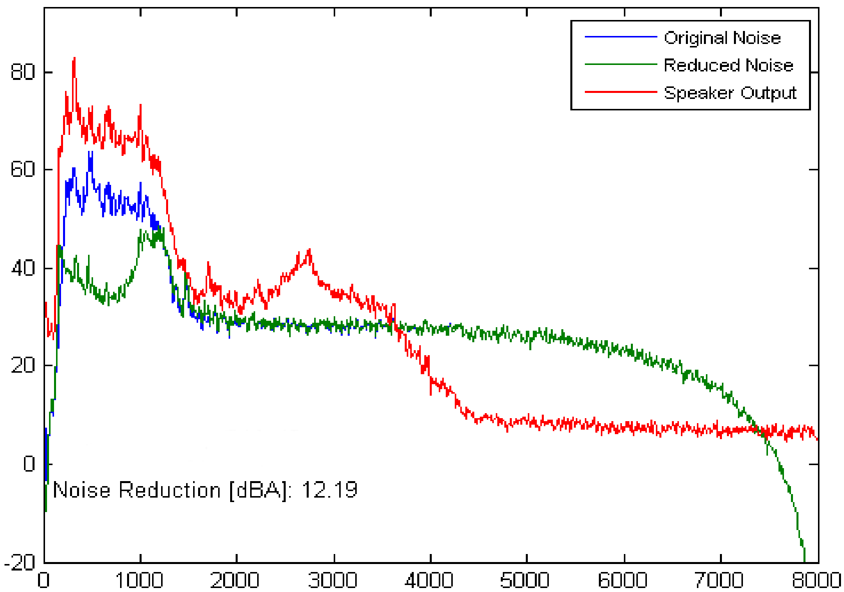


Fig 4-10 Simulation Result for Earth auger

On the contrary, the equipment that generates an impact sound, such as rock drills, jack hammers, and pump cars, has a noise cancellation effect of

2.1dB~5.9dB. This is a deficient result compared to other construction equipment. In addition, there were cases in which the noise level was increased in the process of the experiment. Fig 4-11 indicates the ANC simulation results for jack hammer.

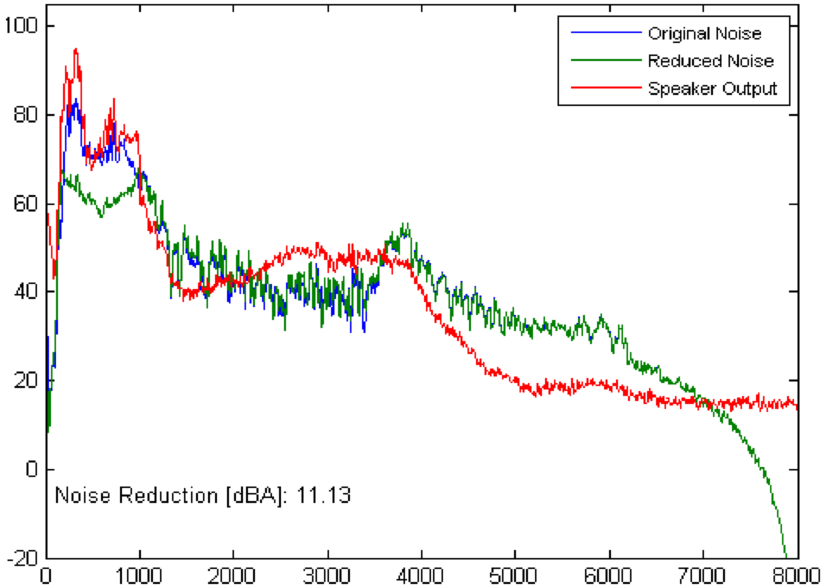


Fig 4-11 Simulation Result for Jack hammer

When active noise control was applied to jack hammer, a sound pressure level of 78.3dB~80.3dB was measured. As a result, a noise cancellation effect of about 5dB was confirmed, and this result was compared to sound pressure level of 83.6dB~86.1dB in which active noise control was unapplied.

Fig 4-12 shows the ANC simulation results of multiple noises generated from bulldozer, excavator, and dump truck, and simulation result indicates that noise level of 8.2dB~9.8dB was reduced compared to the sound pressure level which active noise control was unapplied. This is because multiple noises generated from equipment such as bulldozer, excavator, and dump truck include a great deal of low-frequency sound. Further, noise cancellation effect was efficient as the ANC measurement value approximate 79% of the ANC simulation result despite the environmental constraints.

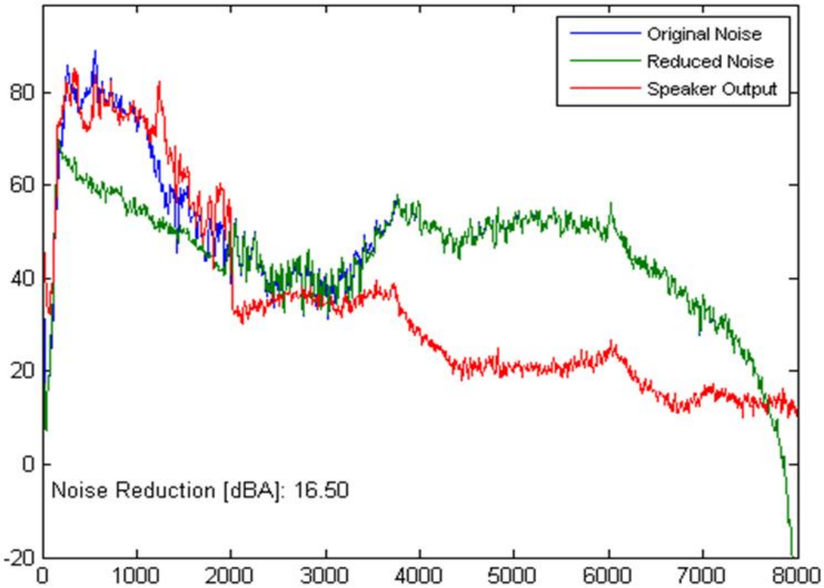


Fig 4-12 Simulation Result for Multiple Noise

However, there was a general tendency for the ANC measurement value to be deficient compared to the ANC simulation results. This is because there are environmental constraints, including background noise, and construction equipment that generates an impact noise such as pile drivers and breakers mainly makes high-frequency noise.

According to work type, high noise cancellation performance was confirmed in earth and grading work, foundation work, and concrete work in which many complaints and disputes have occurred.

In the case of earth and grading work, it is possible that the noise level of 7.0dB~10.1dB is attenuated.

The results of this experiment can be used as the basis for the ANC management model, and the proper selection of construction equipment when active noise control is applied to construction sites. However, as this experiment was conducted in a single-channel method, the research has a limitation of the performance of noise cancellation as compared to multi-channel method using several speakers and microphone.

Furthermore, since the simulation was implemented using a computer, there may be a difference in measurements according to the performance of the speaker. In addition, the experimental environment has differs from actual construction sites. Therefore, if the experiment is performed in a proper environment using multi-channel and spectrum analysis, the effect of active noise control would be greater in reducing the noise generated from construction sites.

Table 4-1 ANC Simulation Results

Work type			Earth and grading work						Foundation work			Frame work		Demolition work			Other work	
Construction equipment			Excavator	Bulldozer	Wheel loader	Grader	Vibrating roller	Vibrating compactor	Earth auger	Boring machine	Pile driver	Concrete mixer	Concrete Pump car	Rock drill	Jack hammer	Air compressor	Dump truck	Forklift
ANC	Unapplied	Max	86.2	86.1	83.2	84.6	84.8	90	79.4	86.9	88.1	85.4	91	83.3	86.1	86.3	85.8	86.2
		Min	82.2	82.9	79.8	78.3	80.6	86.5	76.9	84.1	73	77.8	84.4	78.4	84	77.8	79.6	74.8
		Mean	83	84	81.5	79	82	83.2	78	85	76	81	86	81	83.6	81	82	82
	Applied	Max	77.8	78.4	76.3	78.5	77.7	81.4	71.6	77.8	82.2	78.4	86.6	81.2	80.3	79.7	75.2	80.8
		Min	75.2	76.5	73.2	71.3	74.5	78.5	66.8	74.9	68.6	71.9	78.5	76.4	79	69.4	68.7	68.2
		Mean	76	78	74.3	73	75	77.3	68	76	72	74	82	79	78.3	77	72	75
① Maximum Effect by Measuring			8.4dB	7.7dB	7.2dB	7.0dB	8.6dB	10.1dB	10dB	5.9dB	6.2dB	7.0dB	5.9dB	2.1dB	5.8dB	8.4dB	10.9dB	7.0dB
② Optimal Effect by Simulation			11.8dB	8.7dB	9.3dB	10.7dB	11.2dB	10.5dB	12.1dB	15.8dB	8.1dB	9.7dB	8.9dB	12.6dB	11.1dB	11.7dB	13.7dB	8.8dB
③ Variation(=②-①)			3.4dB	1.0dB	2.1dB	3.7dB	2.6dB	0.4dB	2.1dB	9.9dB	1.9dB	2.7dB	3.0dB	10.5dB	5.3dB	3.3dB	2.8dB	1.8dB

4.5 Summary

In this chapter, ANC management was suggested, and the contents for applying active noise control to each process were explained. In addition, ANC simulations were performed to ensure the applicability of active noise control to construction sites.

The ANC management model suggested in this study has three steps: pre-planning, simulation, and implementation. The proposed management model can be helpful to reduce noise and the number of disputes related to construction noise.

In addition, it was confirmed that noise cancellation is efficient at the low and mid-frequency bands below 1000Hz based on the results of the simulations. However, the noise cancellation performance declined as the frequency increased, and the noise was not attenuated effectively at high-frequency bands.

Chapter 5. Conclusion

There are a variety of noise sources on construction sites, and there have been many disputes and complaints due to the noise generated from construction. Thus, many efforts have been tried to reduce construction noise. However, the traditional method, which depends on soundproof walls, has a limited ability to attenuate such noise. Therefore, in this study, the applicability of active noise control is assessed through the experiment and a noise management model using the active noise control technique is suggested to reduce the noise generated from construction sites and to complement the limitations of passive noise control.

5.1 Result and Discussion

This study suggests a management model for applying active noise control to construction sites and reviews the applicability of active noise control through the experiment.

The ANC Management model for construction sites has three steps as follows:

(1) It is important to identify the nature of noise generated from construction sites and acoustical environment. The noise level is predicted by operating a simulation based on the location, the number and the usage time of equipment, background noise, conditions of nearby areas from the drawings and scheduling information. According to the simulation results, the

areas where damages are likely to be occur must be managed and designated as object to be managed by priorities

(2) Based on the characteristic of noise sources, it is necessary to determine a suitable control method and location by considering factors such as site conditions and the target range and surroundings.

(3) The arrangement of the system should be carefully considered, as it plays an important role in the performance of active noise control. After the deployment of a system such as the noise source, control source and speaker is properly positioned within a critical range, the simulation of active noise control is implemented.

To identify the applicability of active noise control to noise generated by construction equipment, 16 types of equipment were selected and ANC simulations were conducted using noise sources collected from the equipment.

The ANC simulations should be performed so that the measurement value applying active noise control approximates the simulation results by changing the system's arrangement, as well as the location and the method of control. Further, this simulation should be carried out until meeting the appropriate noise level or the target noise level, and simulation results are as follows.

(1) Based on the results, noise attenuation appeared to be effective in frequencies below 1000Hz, and as the frequency band increased, the noise cancellation effect of active noise control decreased.

Further, the noise cancellation performance was reduced as the frequency is increased. Noise cancellation effect decreased at high-frequency bands above 8000Hz.

(2) In Particular, it was confirmed that the cancellation effect was excellent for equipment such as earth augers, vibration rollers, dump trucks, and excavators generating noise caused by engine rotation.

(3) However, in the case of equipment that generates an impact sound such as rock drills, jack hammers, and pile drivers, the effect of noise cancellation is lower than other construction equipment.

(4) Further, it was confirmed that the performance of cancelling noise is remarkable for earth and grading work, foundation work, and frame work. In particular, the simulation results show that the noise level of 7.0dB~10.1 can be attenuated depending on the equipment.

There is a difference in performance of noise cancellation depending on the equipment. This is because many types of equipment have dissimilar noise features. In particular, equipment that generates an impact sound does not have a significant noise cancellation effect, as such equipment has a high-frequency sound.

5.2 Contributions

The availabilities of the management model using active noise control are as follows.

The ANC management model is effective in reducing low-frequency as well as high-frequency noise. Passive noise control, which blocks the propagation of noise using soundproof walls, is focused on high-frequency noise, it has a limitation to reduce low-frequency noise. However, if active noise control is applied to construction sites, it can reduce the noise of a broad frequency band and alleviate people’s suffering and stress. As a result, it is expected that the number of disputes and complaints filed will decline.

Further, the proposed ANC management model could not only be helpful to attenuate the noise level generated at construction sites, but also to reduce side effects such as delays and stops of project as well as the payment of compensation. It also allows for construction projects to be progressed in accordance with their expected schedule. In addition, it has the potential to significantly improve the quality of people’s lives.

However, it is essential for signal processing techniques to be advanced to apply active noise control on construction sites, and the techniques need to expand the effect of noise cancellation from a limited area to a wider range.

5.3 Limitation and Further Study

This research is not through a process of applying active noise control to the actual cases. Therefore, research on how much noise is reduced by applying active noise control and the effect of active noise control in reducing the stress of local residents is insufficient. In addition, because these experiments are conducted in a single-channel, the performance of active noise control is limited compared to the multi-channel method.

Furthermore, there are differences between the experimental conditions and the site conditions in which construction is actually carried out, as the noise level is measured coming out through the S-fan90 duct rather than noise that is emitted in a spherical shape.

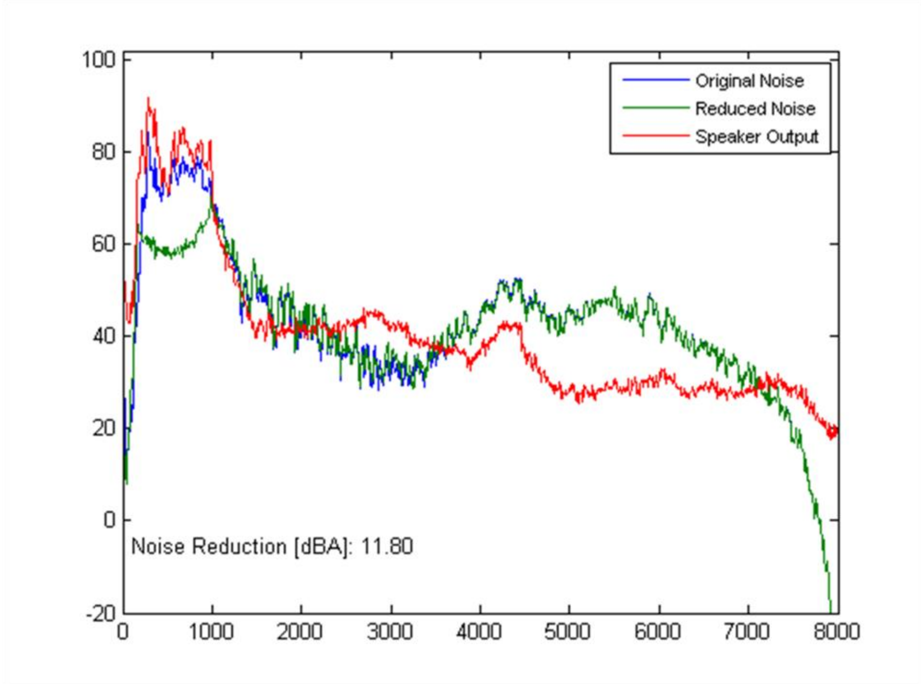
Therefore, additional experiments should be implemented to achieve more substantial results under conditions similar to actual construction sites, and ANC simulation should be implemented in accordance with detailed procedures.

Appendices

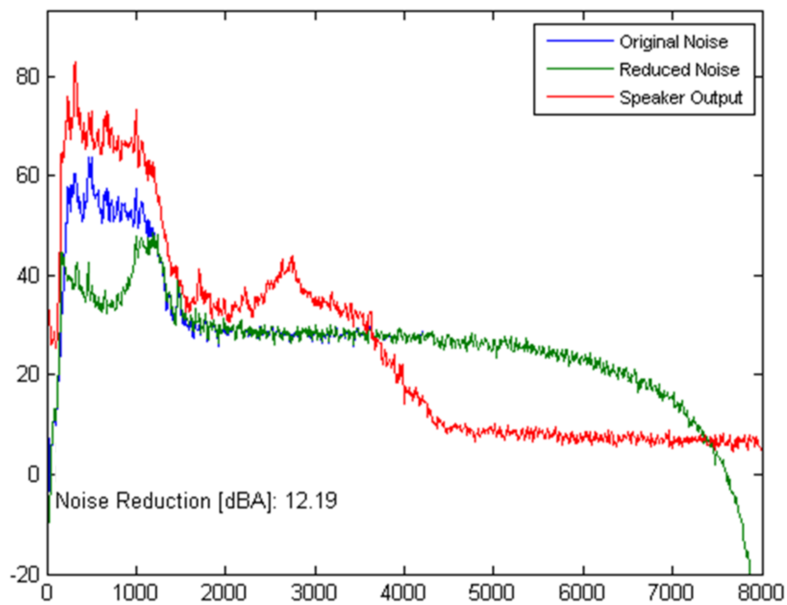
Appendix A. Simulation Results of Active Noise Control

Appendix B. ANC Software Interface

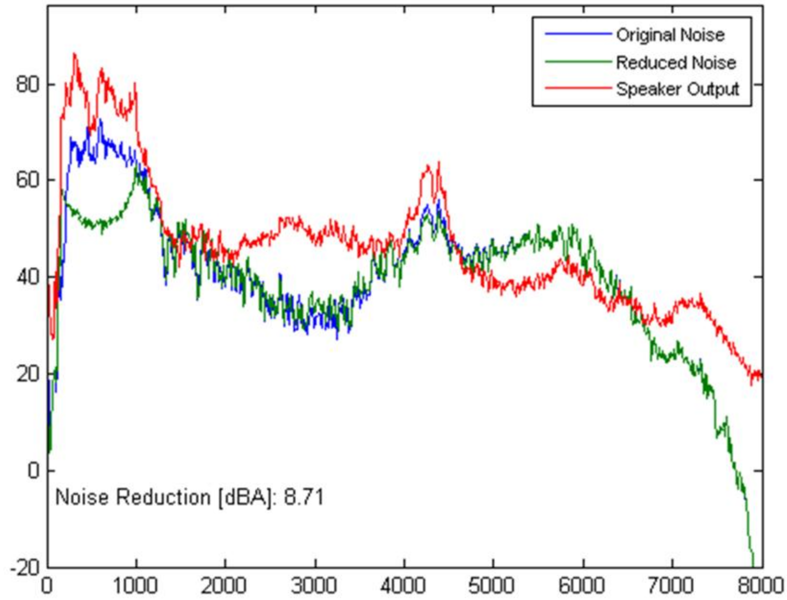
Appendix A-1 Simulation Result : Excavator



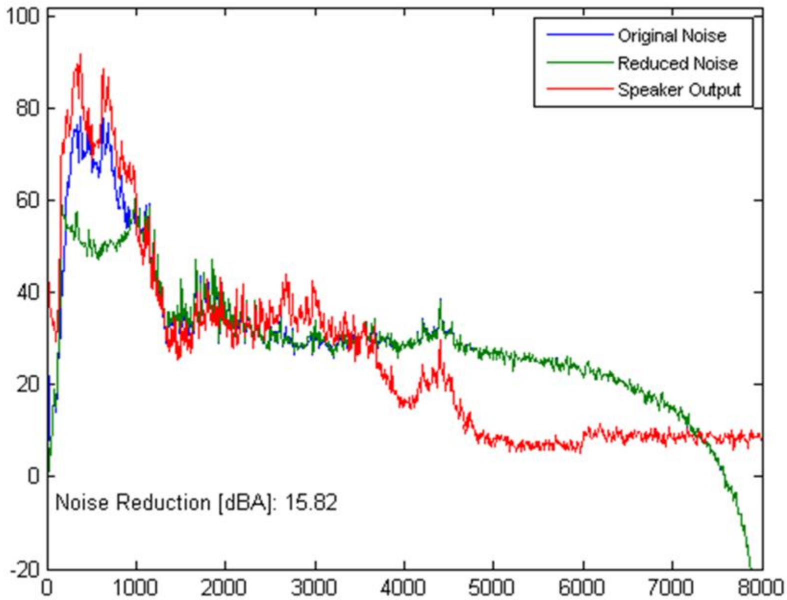
Appendix A-2 Simulation Result : Earth Auger



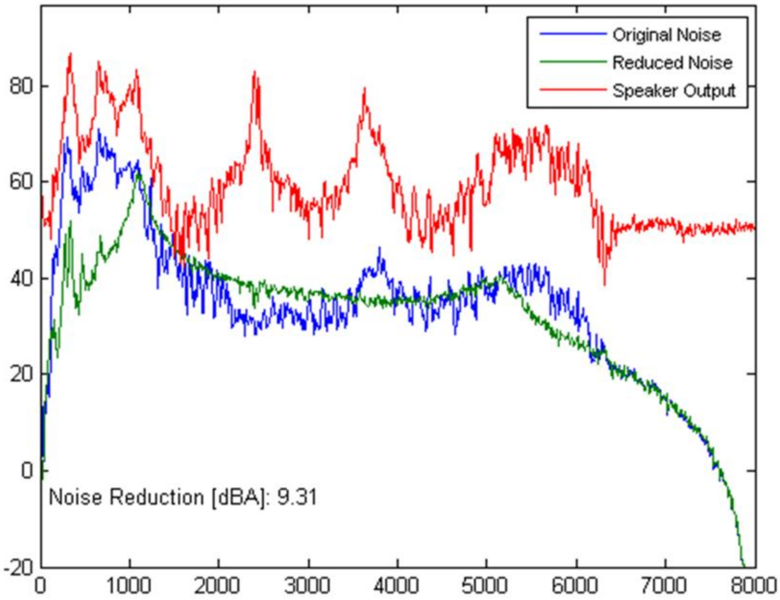
Appendix A-3 Simulation Result : Bulldozer



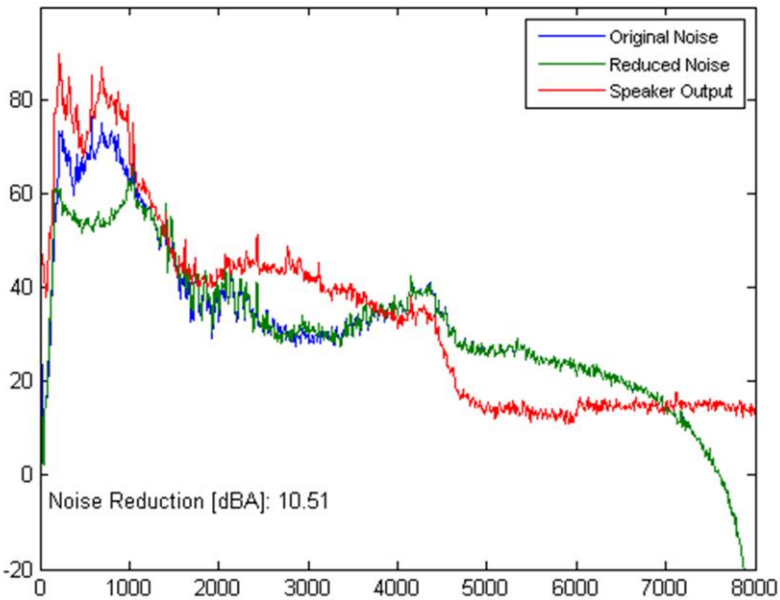
Appendix A-4 Simulation Result : Boring Machine



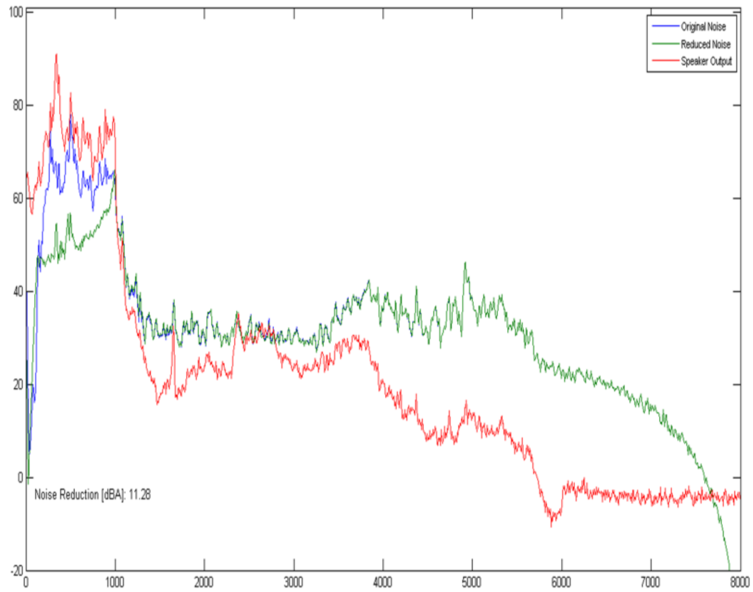
Appendix A-5 Simulation Result : Wheel loader



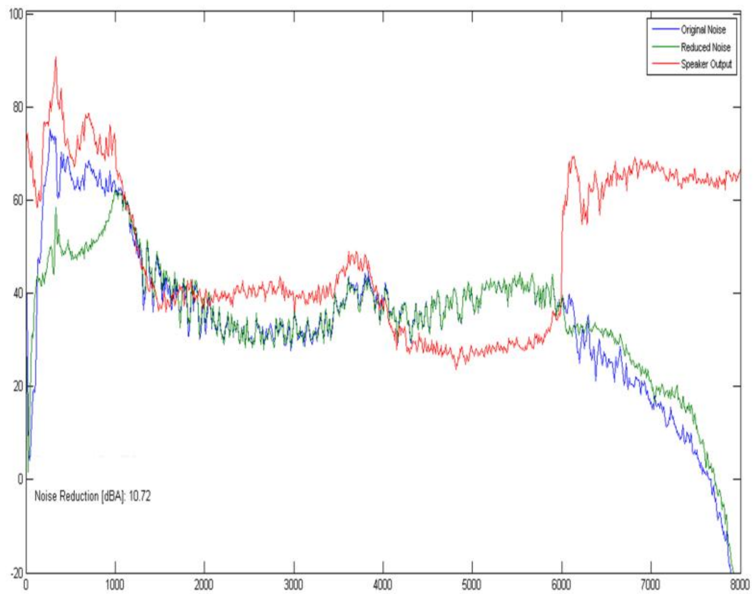
Appendix A-6 Simulation Result : Vibrating Compactor



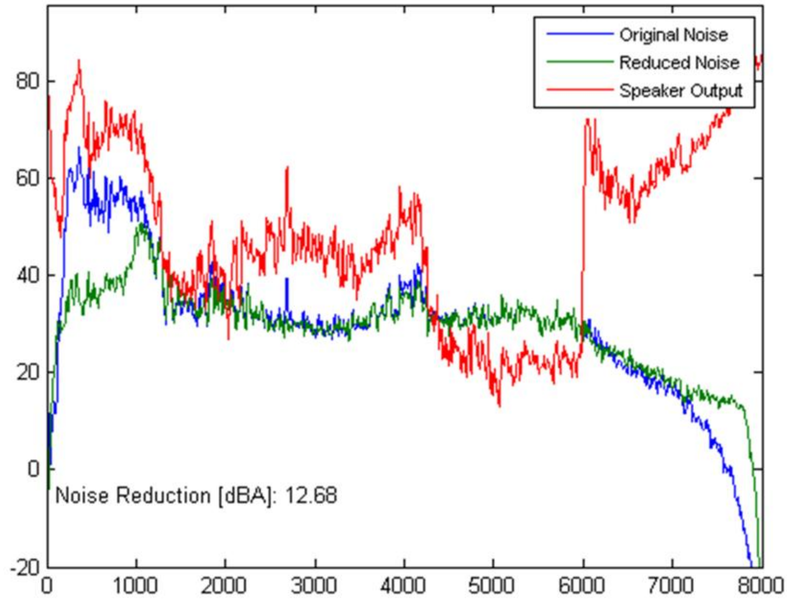
Appendix A-7 Simulation Result : Vibrating Roller



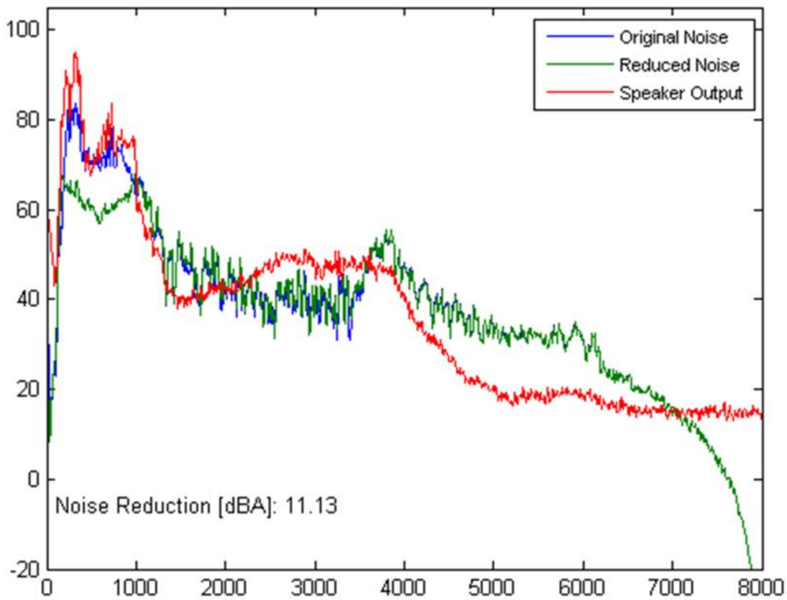
Appendix A-8 Simulation Result : Grader



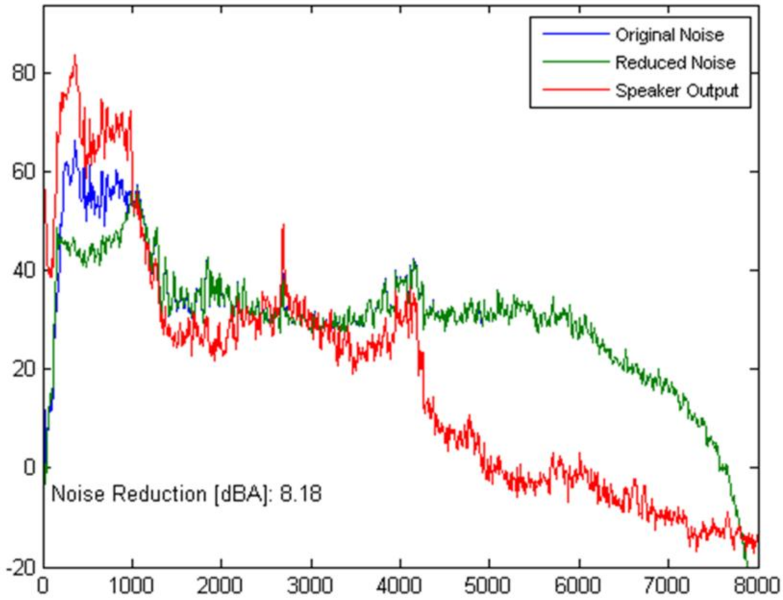
Appendix A-9 Simulation Result : Rock Drill



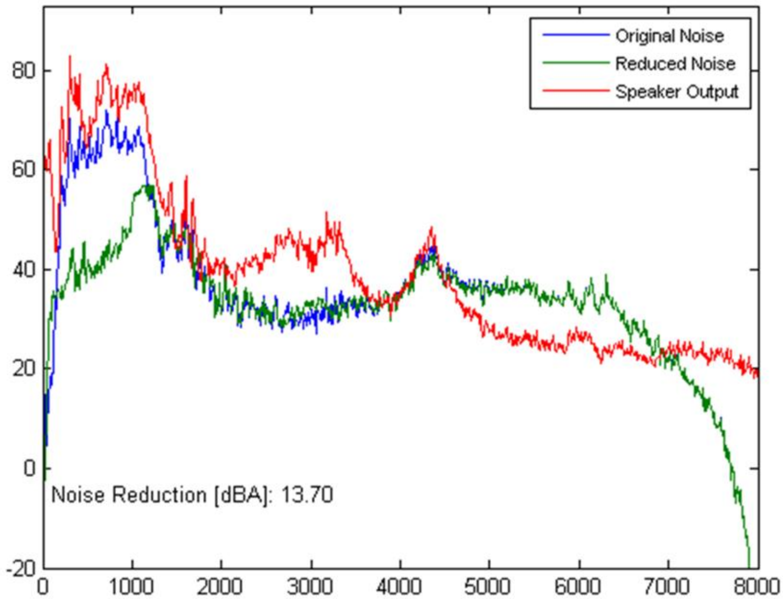
Appendix A-10 Simulation Result : Jack Hammer



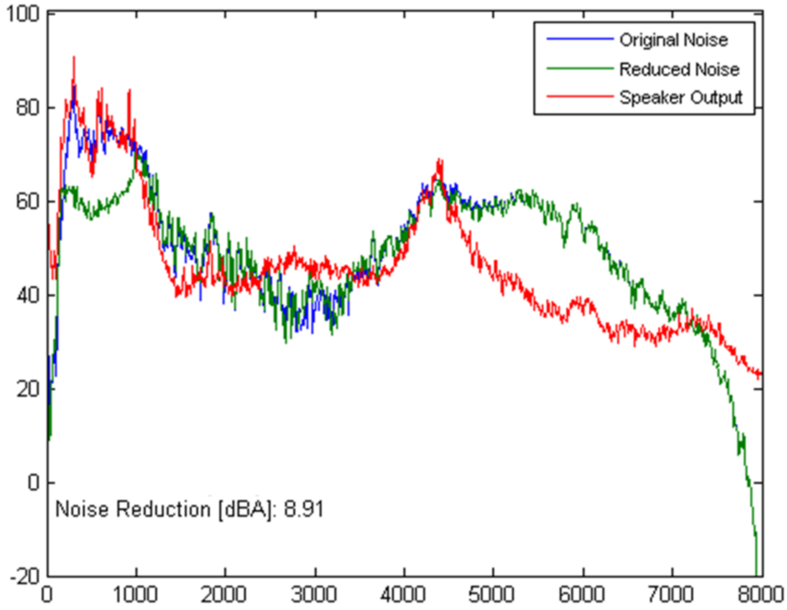
Appendix A-11 Simulation Result : Pile Driver



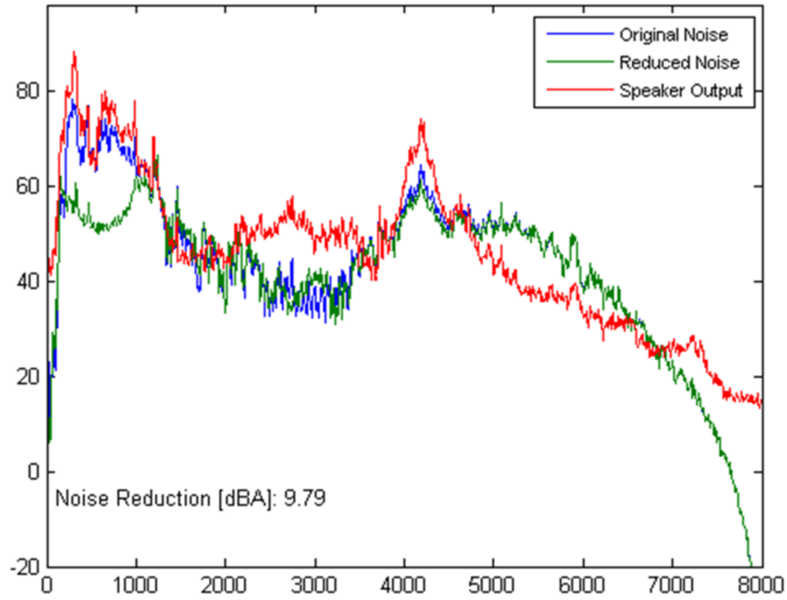
Appendix A-12 Simulation Result : Dump Truck



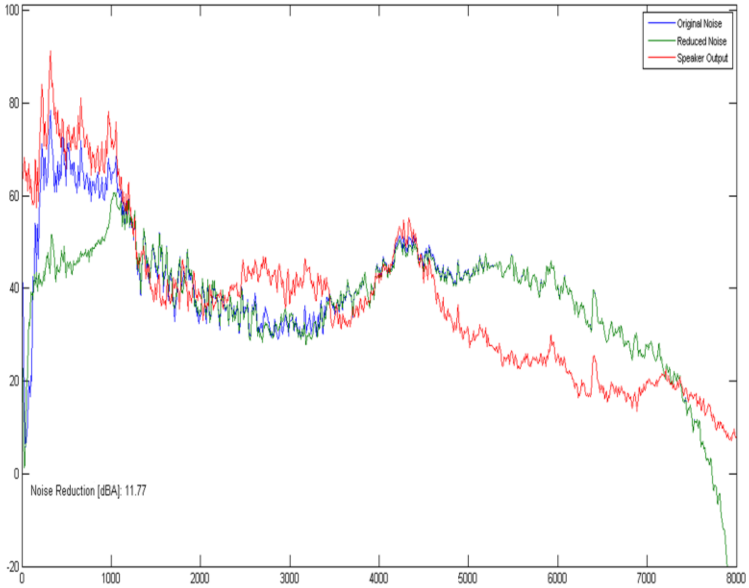
Appendix A-13 Simulation Result : Concrete Pumpcar



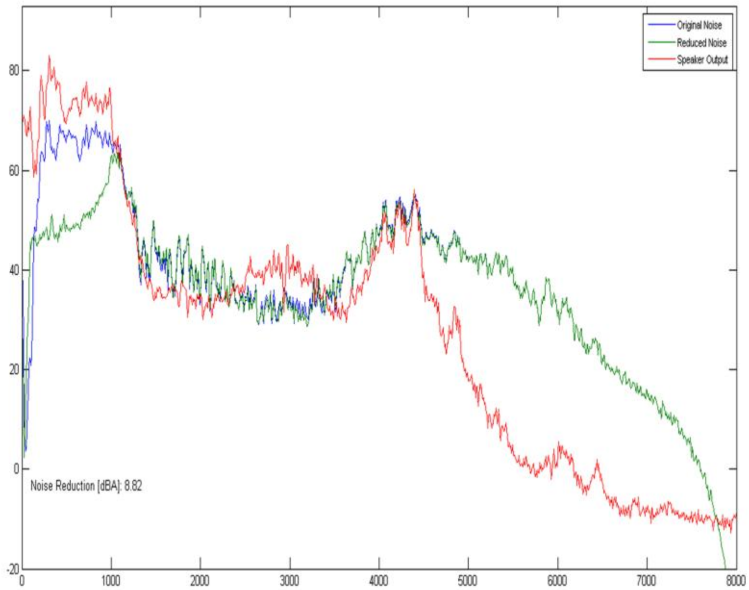
Appendix A-14 Simulation Result : Concrete Mixer



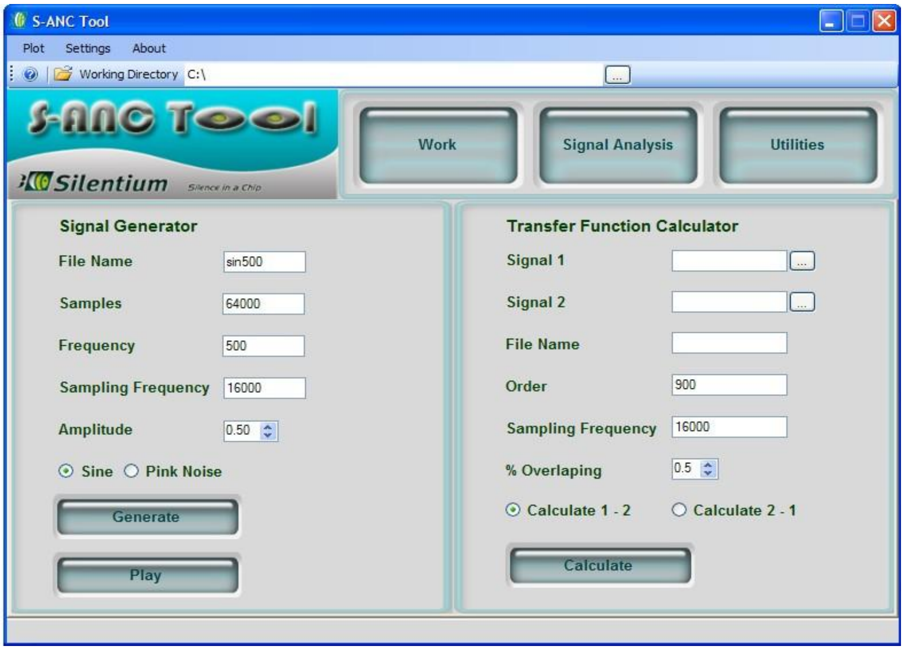
Appendix A-15 Simulation Result : Air Compressor



Appendix A-16 Simulation Result : Forklift



Appendix B-1 ANC Analysis Software



Appendix B-1 S-Cube Interface

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국 문 초 록

건설현장에서 발생하는 소음으로 인하여 많은 사람들이 고통을 겪고 있고, 그로 인하여 민원과 분쟁이 증가하고 있다. 이러한 민원은 사업의 지연 및 중단, 배상액 지불과 같은 시간적, 경제적 손실을 초래하므로 엄격하게 관리되어야 한다. 이러한 배경 하에 정부는 제2차 생활소음 줄이기 종합대책을 통하여 기존 방음벽 중심의 소음정책에서 탈피하고 발생원 중심으로 소음을 관리하기 위해 노력하고 있다. 그러나 건설소음은 일시적이고, 불규칙적으로 발생하며, 건설장비 자체의 소음레벨이 높기 때문에 쉽게 제어되기 어렵다. 또한 최근 선진국을 중심으로 사람들에게 쉽게 인지되지는 않지만, 고주파 소음과 마찬가지로 인체에 정신적, 신체적 피해를 주는 저주파 소음에 대한 연구를 활발히 진행하고 있다. 그러나 이러한 노력에도 불구하고 방음벽을 이용하는 기존의 수동적인 소음관리방식으로는 다양한 소음원이 복합적으로 존재하고 있는 건설현장에서 고주파 소음을 저감하는데 효과가 있을 뿐, 저주파 소음을 저감하는데는 한계가 있다.

타 산업에서는 소음을 저감하는 새로운 방법으로 능동소음제어에 대한 연구가 활발히 진행되고 있다. 능동소음제어는 소음을 그 신호와 같은 진폭, 역위상을 갖는 음을 인위적으로 발생시켜 소음을 상쇄시키는 방법으로서, 방음벽을 주로 이용하는 기존의 수동적인 소음관리방식의 보완책으로서 시도되고 있다. 그러나 건설산업에서

능동소음제어를 이용하여 건설현장에서 발생하는 소음을 저감하기 위한 연구는 부족한 상황이다.
그러므로 본 연구는 건설현장에서 발생하는 소음을 저감하고, 기존의 수동적인 소음관리방식의 한계점을 보완하기 위한 방법으로 능동소음제어를 이용하여 건설현장에서 발생하는 소음을 저감하기 위한 관리모델을 제안하는 것을 목적으로 한다. 능동소음제어 관리모델은 크게 계획단계, 시뮬레이션 단계, 적용단계의 3단계로 구성된다. 또한 능동소음제어의 건설장비 적용성을 검토하기 위하여 능동소음제어 시뮬레이션을 수행하였다. 실험의 결과, 1000Hz이하의 주파수 대역에서 능동소음제어의 효과가 두드러졌고, 주파수 대역이 증가할수록 상쇄의 성능은 줄어드는 것을 확인하였다. 장비별로는 어스오거, 진동롤러, 굴삭기, 공기압축기, 덤프트럭과 같은 장비에서는 소음의 상쇄가 비교적 원활하였으나, 브레이커, 펌프카와 같은 충격성 소음을 발생시키는 건설장비에 있어서는 소음을 상쇄하는 성능에 있어서 한계를 보였다.
본 논문은 능동소음제어를 통하여 건설현장에서 발생하는 소음을 저감하여, 소음관련 민원과 분쟁을 최소화하고, 기존의 수동적인 소음관리방식을 보완하는데 일조할 수 있을 것이라 기대한다.

주요어: 능동소음제어, 능동소음제어 시뮬레이션, 저주파 소음, 소음관리모델, 소음제어, 건설소음.

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