Project Title

ENGINEERING CONTROL OF LONGWALL MACHINE NOISES

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ABSTRACT

Longwall mining is a highly productive and very safe mining method employed in underground coal mine. In recent years, about 52 coal mines employing longwall mining method account for more than 50% of underground coal production while nearly 1,000 room and pillar mines make up the remaining production. However, due to the high degree of mechanization and the confined environment, noise levels at longwall mining faces are normally high. Constant exposure to such a noisy environment for an extended period could lead to permanent hearing loss for the workers. The two major sources of noise in a longwall face are: (1) the machine noises produced by the mining machines, and (2) the background noises produced by the breakage and movement of surrounding rock strata in the process for them to reach a new equilibrium after being disturbed by the mining activities. The machine noises contribute the major portion of the noise exposures to the workers. The background noise is a piece of very useful information for the workers to detect and predict harmful ground movement events. Therefore, it is desirable to leave the background noise intact.

The main objectives of this research are: (1) to characterize the noise environment in longwall mining with the particular emphasis on the noise sources generated by various mining machines, (2) to identify the main noise sources that the miners are exposed to, and (3) to develop engineering controls to reduce noise exposure in longwall working faces.

The main tasks performed in this research are:

(1) *Noise surveys in two longwall coal mines*. In conducting the field surveys, noise dosimeters were used to measure the noise level (signified as sound pressure level or SPL) along the longwall faces as well as at various job-related activities. The sound meters were used to perform the Octave Band Analysis (OBA) so that the frequency distribution of the noise sources can be determined. During the field trips, noise from mining machines was also recorded using a high fidelity sound recorder for laboratory analysis and experiments.

(2) *Laboratory analysis and experiments*. The recorded noise segments were analyzed using Oros analyzer to examine the frequency spectrum of various machine noise sources. The analysis results were also used to identify the significant noise sources.

(3) *Development of Active Noise Cancellation (ANC) Technology for stage loader*. The field surveys showed that the stage loader, a piece of machine located at the end of the longwall face where the loose coal is crushed and transferred to a belt conveyor, is the most noisy machine in a longwall face. Its enclosed compartments are good candidate places for applying the ANC technology. A range of noise reduction methods including ANC method have been experimented on a retired stage loader denoted by a mining company with the recorded noise segments. Significant reduction in noise level have been achieved with proper ANC setups and operating parameters.

In this final report, the methodologies of and the instruments for the field noise surveys are described. The frequency contents as well as the associated working activities of the identified significant noise sources resulted from the field surveys and laboratory analyses in the longwall faces are presented. Based on these findings, ANC setup was prepared for canceling the noise waves in a range of sound frequency and reducing the overall sound pressure level for the most noisy machine in the longwall faces – the stage loader. The experimental setups and the range of operating parameters for the ANC technology to be effective in reducing overall noise for the stage loader are explored and the effectiveness of the ANC in such application is studied.

LIST OF TABLES

SECTION 1

Highlights/Significant Findings

This research project is to develop and test a technology for the reduction of the overall sound levels of machine noises in the underground longwall faces while keeping the background noise basically unaltered. The most significant findings achieved from this research are:

- Field noise surveys have been conducted to characterize the noise field in and around the longwall faces. It is found that the crusher/stage loader assemblies are usually the noisiest machines in a most congested area in the longwall face. The octave band analysis showed lower frequencies (100 Hz -650 Hz) as dominant frequencies.
- The crusher/stage loader is selected for ANC application. Extensive and systematic laboratory experiments have been conducted on the noise segments recorded from longwall stage loaders. The experiments have shown that the ANC can achieve significant noise reductions if proper control parameters have been used. The frequency range within which the noise reductions are significant is from 100 Hz to 650 Hz – consistent with the dominant frequency range of most longwall noise sources. The overall noise reductions are in the range from 5.5 dB to 9.3 dB.
- However, the ANC was not very effective in reducing the portion of the noise in frequency higher than 1,000 Hz at the current stage of our research. A combined approach using both the active and passive noise (more effective for high frequency noise) controls would be preferred.

Translation of Findings

In the last three decades, statistics have demonstrated that most illnesses and injuries associated with mining have been greatly improved except for hearing loss caused by overexposure of noise. The use of heavy machineries, breakage of hard rocks, and the confined working spaces are some of the factors that contribute to high levels of noise exposure in mining. According to NIOSH data (Bauer, 2001a), about 80% of US miners are working in environment where the time weighted average (TWA) noise levels are higher than 85 dBA while about 25% of the miners are exposed to a TWA noise level higher than 90 dBA. Another NIOSH study on a large sample of audiograms among coal miners, non-coal miners and non-exposed males (Franks, 1996) shows that about 90% of coal miners suffered noise-induced hearing loss significant enough to be classified as a hearing disability by the age of 51. The percentage of hearing impairment for the coal miners is much higher than those for the metal/nonmetal miners (62%) and non-exposed males (10%). NIOSH has recognized noise induced hearing loss (NIHL) as one of the criti¬cal area in the National Occupational Research Agenda (NORA).

Longwall mining is the safest and the most productive underground coal mining method. However due to its high degree of mechanization in a relatively small confined space, noise level at a longwall face is normally high with the noises produced by the mining machines making up most of the noise. Workers at longwall faces could be the group of coal miners with even higher risk to develop permanent hearing loss.

This research project is to develop cost effective technology to reduce noise exposure to the longwall miners. The two important tasks are: characterizing significant noise sources, and developing appropriate methods to control the noises.

Main Task No. 1: Noise Characterization

As in any studies for industrial noise control, the emphasis should be first placed on finding and characterizing the noise sources. This important task was carried out by conducting field noise surveys in two selected longwall faces as well as laboratory analyses of recorded noise segments.

In the field noise surveys, a number of noise measurement instruments and techniques were used. Sound level meters were used in two different stages for different purposes. In the first stage, sound level meters were used to measure the sound pressure level (SPL) at the various positions in and around the longwall face. The survey results were used to plot the profile of SPL in the area so that the significant noise sources can be determined. In the second stage, the sound level meters were used to perform 1/3 octave band analysis (OBA) at various points of interest in the face. The OBA analysis provides very useful information about the acoustic energy (sound intensity) distribution in the possible frequency range for the identified noise sources. Such information is especially useful for the design of engineering noise controls.

Five sets of logging dosimeters were used to measure the noise exposure dosage for different machine operators, the sound pressure level (SPL) distribution around a number of mining machines. The field surveys showed that the stage loader is one of the noisiest mining machines in the longwall faces.

One high quality sound recorder was also used in the field surveys to record noise segments at the selected noise sources so that OBA analyses can be analyzed more accurately and efficiently with laboratory equipment. The recorded noise segments were also used in laboratory for experimenting various noise control strategies and technologies.

Main Task No. 2: Development of Noise Control Technology

Based on the characteristics of the noise sources in the longwall faces, efforts have been made to develop engineering controls to reduce the noise levels for the major noise sources and the working locations where the miners spend most of their times. There are two possible approaches to reduce the noise: passive and active. The passive noise controls could be costly, require large space and are ineffective at low frequencies, making some of the passive control methods often impractical. In this research, the emphasis is placed on studying the applicability and effectiveness of the active noise cancellation (ANC) technology for the crusher/stage loader assembly. Experiments have been performed to apply the ANC technology on a retired stage loader. With proper equipment setups and operating control parameters, a significant reduction in sound pressure level can be achieved.

Outcomes and Impacts

The field noise surveys conducted in this research provided valuable sound intensity and spectrum distribution information about the significant noise sources in the longwall faces. In addition to passive noise controls, efforts to apply a new technology, active noise cancellation method, in reducing the noise level around stage loader have been explored and achieved some significant reduction.

SECTION 2

SCIENTIFIC REPORT

CHARACTERIZATION OF NOISE AND DESIGN OF ACTIVE NOISE CONTROL TECHNOLOGY IN LONGWALL MINES

CHAPTER

1 INTRODUCTION

1.1 Backdrop

In the last 25 years, statistics have demonstrated that most illnesses and injuries associated with mining have been greatly improved except for hearing loss caused by overexposure of noise. The use of heavy machineries, breakage of hard rocks, and the confined working spaces are some of the factors that contribute to high levels of noise exposure in mining. According to NIOSH data (Bauer, 2001a), about 80% of US miners are working in environment where the time weighted average (TWA) noise levels are higher than 85 dBA while about 25% of the miners are exposed to a TWA noise level higher than 90 dBA. Figure 1-2 shows the results of a NIOSH analysis of a large sample of audiograms among coal miners, non-coal miners and non-exposed males (Franks, 1996). Among these three groups, about 90% of coal miners suffered noise-induced hearing loss significant enough to be classified as a hearing disability by the age of 51. The percent-age of hearing impairment for the coal miners is much higher than those for the metal/nonmetal miners (62%) and non-exposed males (10%). NIOSH has recognized noise induced hearing loss (NIHL) as one of the critical area in the National Occupational Research Agenda (NORA).

In the coal mining industry, the underground coal miners are expected to experi-ence higher noise levels, because of the confined working environment, than those by the surface miners. In underground coal mines, the longwall mining is the safest and the most productive mining method. In recent years, about 60 longwall installations pro-duces about one half of the total US underground coal production. Longwall productivity is at least five times that of the commonly used room and pillar method, and is at least 200 times safer in terms of fatalities and lost-time injuries. However due to its high de-gree of mechanization within a relatively small and "hard" confined space, noise levels at longwall faces are normally very high. Table 1 shows the statistical data extracted from a large MSHA noise dosage survey database. This database contains nearly 8,000 noise dosage records surveyed in US underground and surface coal mines during the time pe-riod from October 1999 to July 2000 (MSHA, 2000a). The data in Table 1-1 are for those operators of heavy mining machineries in underground coal mines - the groups of under-ground miners expected to work in more noisy environments than the others. The col-lected data represent the noise levels in the working environments without the reduction effects of ear muffs or ear plugs. The data show that both the average noise dosage and the percentage of overexposure in the longwall faces are higher than those in other ma-chine intensive environments. One possible reason is that the machines used in the longwall face (i.e., shearer, crusher, stage loader, armored face con-veyor, shields, panel belt conveyor) have much higher horsepower settings than those in the other mine work-ings. As an example, among the 59 US longwall installations in 1999 the average horse-power on the shearer was 1,180 hp with the highest horsepower to be 2,091 hp (Fiscor, 2000). By contrast, the power ratings of the continuous miners, used in room-and-pillar mining operations, are normally around 500 hp.

Table 1-1 MSHA Noise Survey Results Among Occupations (1999-2000)

Occupation	# Re-cords	Type of Dose	Max.	Average	Std Dev.	Over Limit
Longwall Shearer Operators	61	90 PEL Dose	521.2	177.0	105.5	73.8%
		85 Action Dose	678.6	137.9	90.2	62.4%
Continuous Miner Operators	702	90 PEL Dose	1368.0	126.9	100.4	54.3%
		85 Action Dose	678.6	137.9	90.2	62.4%
Twin Head Bolter Operators	418	90 PEL Dose	778.5	83.0	64.9	25.1%
		85 Action Dose	700.0	100.5	64.0	39.2%
Single Head Bolter Operators	371	90 PEL Dose	338.9	74.1	53.8	22.6%
		85 Action Dose	687.7	92.9	60.3	35.3%

Although noise is an old problem in underground coal mines, little research has been performed so far. With the ever-increasing machine capacity in the industry, this problem will become more severe in the future. A NIOSH study (Bauer, 2001b) shows that the noisi-est places in a longwall section are near the longwall shearer and the stage loader as shown in

Fig. 1-2. The results also imply that the machine noises contribute to a large portion of the overall noise levels at those areas.

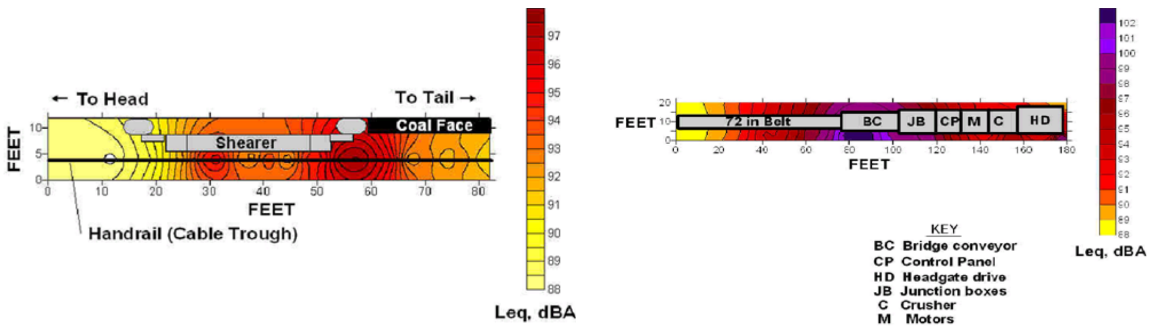


Fig. 1-2 Distributions of Noise Levels Around Shearer (Left) and Stage Loader (Right) in a Longwall Face (Bauer 2001b)

It should be noted that efforts have been made by the equipment manufacturers and by some mine operators to quiet down the machine noises with various passive noise reduction measures such as enclosure, damping, etc. Although such efforts were success-ful in quieting down the working spaces to some degree, the longwall face areas as well as many other underground working areas remain to be very noisy. The current practice is to require all underground miners to wear ear plugs or ear muffs or both to reduce noise exposure. However, MSHA has reported a poor compliance in the use of these protective devices, with about 21.6% of overexposed underground miners not wearing their personal hearing protectors (Seiler, et al, 1994). It is commonly known that miners de-scribe such hearing protectors as uncomfortable and report concerns that it tends to filter out specific noises in the working environment (such as noises associated with breakage of roof rock, rock bursts, etc.) that miners use as safety warnings and operational guides.

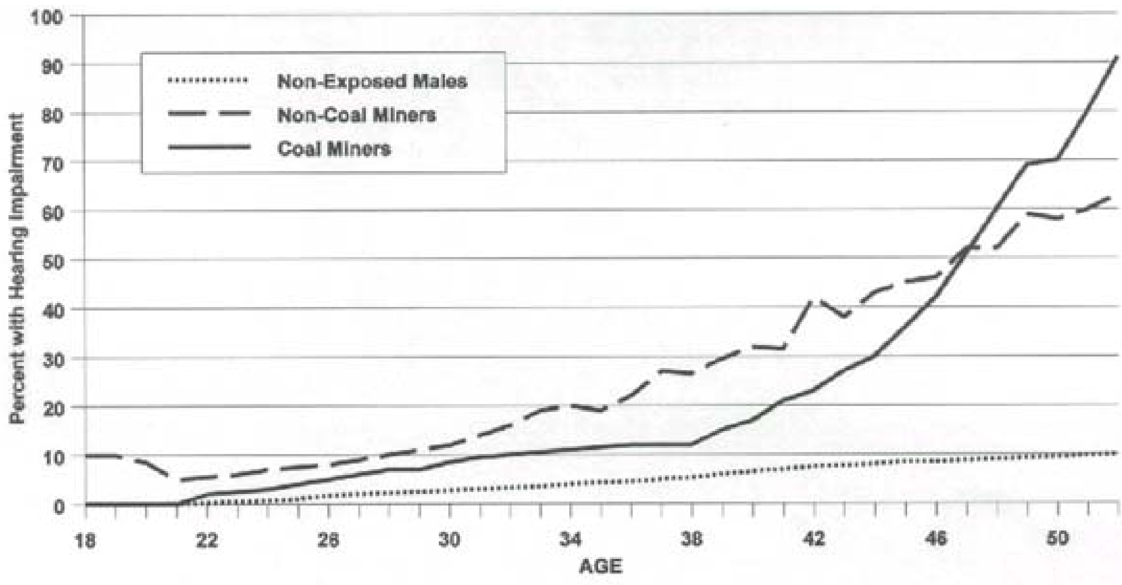


Fig.1.1 *Hearing impairment in coal miners, non-coal miners and non exposed males (NIOSH 1996b, 1997).*

NIHL is a major health issue in the mining industry because the average age of the present workforce is 50 year old and above. Fig 1.2 shows that hearing loss is surely a function of age. Workers with age 50 and more have a hearing loss greater than 25 dB.

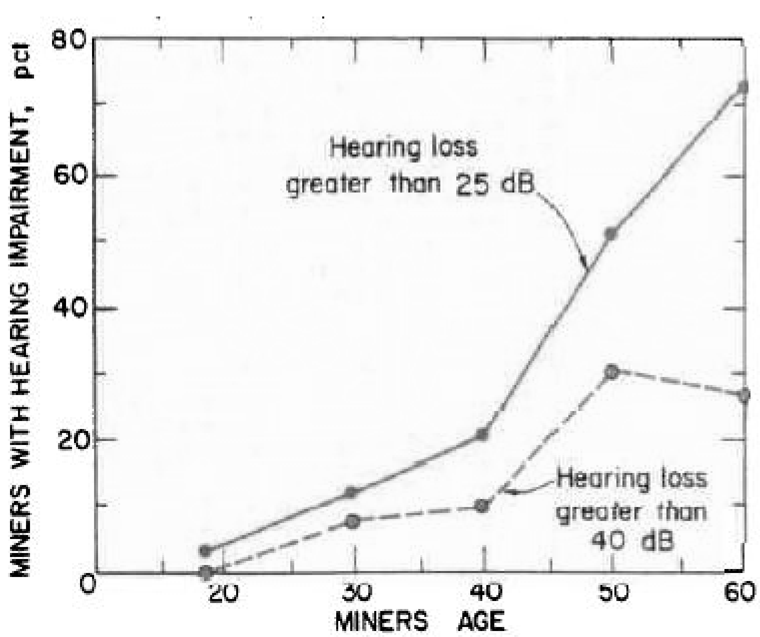


Fig.1.2 *Hearing loss function of age (NIOSH, 1976).*

Longwall mining should enjoy a long and secure future with the present trend. Longwall mines operating in the Pittsburg seam have 6-8 ft thick coal seam. Currently most of the longwall mines have two mile long, 1300 foot wide longwall panel. Shearer, face conveyor and stage loader are the most important production units and consume high power for their operation. E.g. A Joy 7LS2 shearer incorporates 545hp ranging arms, DBT face conveyor is driven by a 350hp motor. Similarly stage loader also need high electric power supply to operate its crusher and other units. Also, in future by using intelligent cutting sequence it is possible that sharer loader productivity can be increased by up to 50% [18]. The reason to mention these machines is to draw a picture of a highly mechanized longwall face with installation of high power consuming machines, which in turn produces a high noise through its operation. These noisy machine operations are developing a health concern among the miners and mine operators.

In order to design and implement effective engineering noise controls, the characteristics of the noise sources and noise fields should be understood. The current research considers the effect of both low and high frequency on the overall sound pressure level in coal mine workings. Additionally, more detailed frequency analysis will be made at different points in the face by octave band analysis (OBA) and sound pressure level (SPL) measurement, which reflects the combined effect of the frequencies. The important aim of this work is evaluation of the active noise cancellation technique on the ground conditions of available model by performing laboratory experiments as this technique is new to the mining industry.

Introduction of faster computer and tremendous advances in the signal processing techniques, it is now possible to incorporate complex random noise signals in any conditions and perform an analysis. Using the state-of-the-art analysis tools available at the time, it has been proven in the past that the frequency and the phase direction of sound pressure level was the main factor responsible for most of the overall noise. Other Industries have already incorporated Active noise cancellation (ANC) technique and some excellent works are available on this issue, but yet mining industry needs more research to be done before a comprehensive understanding of the noise cancellation is developed. This thesis work is an effort to develop the possible application of ANC in mining industry.

1.2 Significance

The problem of noise Induced hearing loss has existed since the Middle Ages; In the professions like blacksmithing seems to have begun as early as 1831 and known to be as "blacksmith's deafness" [4][*]. In World War II, a large number of soldiers returned home with lost hearing. Thus one of the earliest regulations for hearing conservation was Air Force Regulation 160-3, issued in 1948 (Department of the Air Force, 1948). Now, with the advances in the noise measuring techniques that confirm the existence of low and high frequency noise, the sound pressure level in a majority of cases is ascribed to the high frequency noise. This can be witnessed by the deluge of publications on this subject. However, a complete study on the SPL related NIHL should consider both the high and the low frequency noise as the Octave Band Analysis (OBA) in the mines also show the existence of low frequency noise.

Thus equal importance is given to both low and high frequency in this research. Further, the cancellation effects are also investigated for the lower frequency. The combination of active and passive control for low and high frequency respectively could control noise related problems and help the miners to lead a better life. Various studies in the past proved that providing good hearing condition improved on-the-job communication which resulted in high production, lower loss- time accidents and workers maintain good health.

1.3 Objectives

The parameters accountable for overall SPL in an underground mine situation are too many to unite in a research of this level. To make the research easy to handle, limitations have been established on the number of variables and their greatness in significance considered in this thesis. To make the results more practical and meaningful, real time actual mine

[*] Numbers in the square brackets refer to the references given at the end of the thesis

noise condition are developed and the magnitude of the variables similar to underground mining condition are created in the laboratory designs. This research is an earnest attempt to achieve the following broad objectives:

- To study the characteristics of noise field in and around the longwall faces.
- Evaluate the NIHL effects of both low and high frequency noise in underground mining environments.
- Justify logical reason for the need to cancel low frequency noise.
- Enhancing knowledge on the effect of low frequency noise on the overall SPL at the Longwall working faces.
- To develop proper engineering noise control measures and to evaluate their effectiveness for Longwall underground coal mines.

1.4 Thesis Organization

This thesis is arranged into five chapters. Chapter 2 is literature review of on the noise problems and previous researches in characterizing and controlling the noises in the mining industry. Various available techniques adopted in the past to address this issue are discussed and shortcomings delineated. In Chapter 3 deliberations are made about field surveys at different mines to characterize the mine noise in and around the longwall faces. Chapter 4 outlines the results related to the effect of low and high frequency noise on the overall SPL and the criterion for focusing on low frequency for engineering control in this work are provided. Based on this work, guidelines are also developed for choosing proper set-up conditions and parameters for the overall active noise control system. Chapter 4 also includes the discussions on the laboratory experiment set-ups and engineering noise control technique. The effect of cancellation of low frequency noise on the overall SPL is discussed. The list of major conclusions of this work and outline of possible areas for future research work is featured in Chapter 5.

CHAPTER

2 LITERATURE REVIEW

2.1 Introduction

Extensive work on NIHL have been done in the 1970s and 80s. Some of these constitute a broad range of mining conditions. Since the present research is focused at engineering noise control techniques in underground coal mines, only important works related to this topic are reported.

The number of factors governing the noise level in underground mining environment is too many to cover all of them. The complex interaction of all these parameters makes it difficult for any analytical methods to accurately estimate noise pattern state at a point in the mining face. Hence, often the only choice available is to measure the SPL in the field. Thus noise surveys are done in the mines with proper intrinsically safe noise measuring and recording devices [1, 4, and 13].

The mining industry in United States has adopted a number of noise measurements techniques [1, 3, 8, and 10]. These field surveys conducted indicate that the overall SPL in the coal mines is combined effect of low and high frequency noise. The purpose of these field surveys is to characterize the mine noise and acoustic energy distribution in the possible range for proper selection of noise control measure. A brief study has been done in this chapter on the current status of the noise control technology in the US coal mines.

The frequency spectrum analysis provides the knowledge about the influence of low and high frequency noise, particularly, the existence and the effect of low frequency noise; on NIHL in the coal mining industry. Many researchers worked on the problem of noise control and offered explanations based on field and analytical work. In general most of the work was concentrated on administrative noise controls. Low frequency control technology related problems were also reported from Australia [6]. In United States various experiments were completed to develop engineering noise control technology.

The most common noise and engineering controls in others industries include hearing protection devices (HPD) such as ear plugs, ear muffs etc. These HPD are highly dependent on the user interest, motivation and skills. Thus the effectiveness of HPD is very unpredictable for different users. Figure 2.1 shows ear plugs which are commonly used and easily available everywhere. Figure 2.2 shows a type of ear muffs used as HPD.

Fig. 2.1 *Ear Plugs*

Fig.2.2 Ear Muffs

2.2 <u>Literature on Noise Characterization and Noise Cancellation Technology</u>

The engineering control of mine noise through active noise cancellation is a new area for the mining industry compared to other industries. The technology uses the theory of arbitrary mixing of the source noise and anti-noise waves resulting in a sound field with reduced sound pressure level. The principle is patented by Paul Leug in 1934 (U.S.Patent No.2043416). The possible success of the theory was achieved in other industries like aviation; submarines etc prompted the researchers to explore the possibility of its application in the more complicated longwall mining industry. Although very few researcher were noticed working on the noise cancellation technology in mining. Most of them had experienced similar problem of canceling frequencies above 500 Hz.

Bartholomae and Burks studied Longwall mine noise and recommended various solutions to reduce worker noise exposure [3]. Bartholomae also studied the active noise cancellation in various conditions [2].

In 1983, the former Bureau of Mines developed a handbook entitle, “Mining machinery Noise Control Guidelines, 1983”, which was documented by Roy. C. Bartholomae [3]. He did a noise control study on various pieces of mining equipment for dissemination to the mining industry. He proposed several noise treatments methods for different machines in underground mining conditions. Also, Bartholomae presented a paper [2]. He did a data analysis on the longwall face for noise exposure to workers. He plotted noise table for shield setters, shearer operator and headgate operator. The average daily noise dosage (DND) represented in six longwall mines using MSHA DND regulation (90/90/5) are shown in table below:

Table 2.1 *Noise Study with DND*

Occupation Title	MSHA DND (90/90/5)
1. Shearer Headgate	129

2. Shearer Tailgate	126
3. Shield Setter two workers	47
4. Headgate Operator	**70**

To relate his work to present research work, consider case 4 for headgate operator shows 70 dBA for 90/90/5 settings. This is in the critical boundary line with present day MSHA regulation.

Back in 1996, Bartholomae concluded that engineering noise controls be used at longwall face to reduce workers noise exposure. He also pointed out the case of headgate operator to be treated with proper administrative and/or engineering controls.

His work on active noise cancellation performance in hearing protectors showed some positive results for pure tone frequencies. The figure 2.3 shows the repeated procedures of ANC for pure tones at 250, 500, 1000 and 4000 Hz. The results plotted are curves for ANC 'on' and ANC 'off' for the earmuff. Also, a test results for the ANC when safety glasses were placed on the manikin with the set-up are shown in fig 2.4.

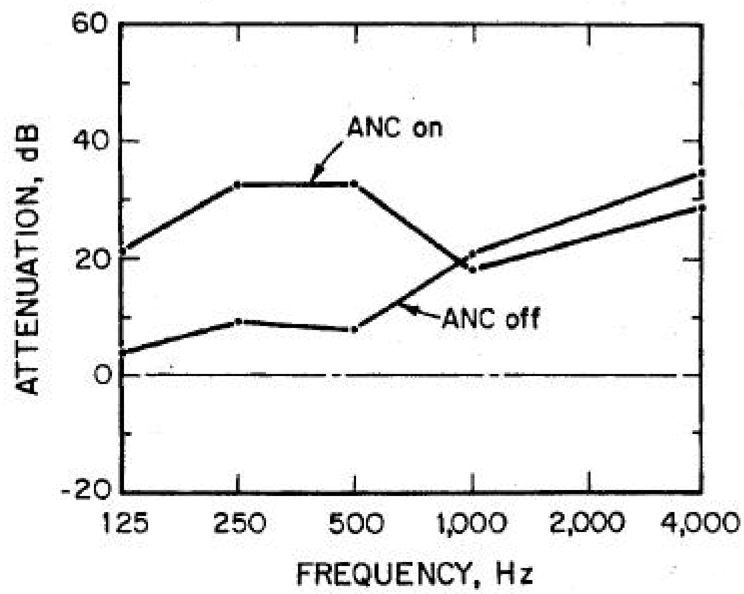


Fig. 2.3 *Kemar Manikin ANCHP attenuation for ANC turned on and off without safety glasses in pure tone, reverberant sound fields. (ref:)*

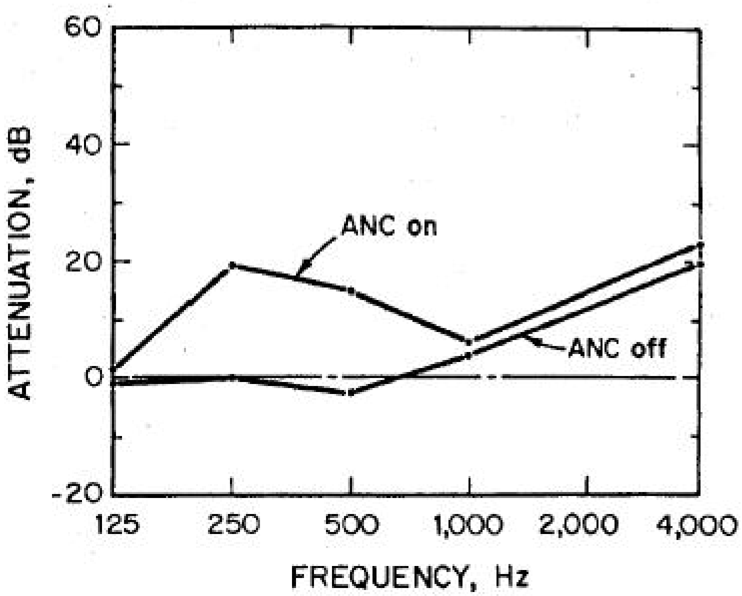


Fig. 2.4 *Kemar Manikin ANCHP attenuation for ANC turned on and off with safety glasses in pure tone, reverberant sound fields. (ref:)*

Although his work explained some broad features of noise exposure and active noise control experiments, it was very rudimentary in its approach. The ANC experiments were done on pure tones conditions which showed some success but the random noise results are not clear from the analysis.

Valoski's investigation [17] of noise exposure in mining industry revealed a good picture for different areas of noise exposure. His research contains statistical analysis based on the data provided by mine operators reporting instances of NIHL. The results presented the temporal distribution of NIHL cases and the occupation and age of miners who incurred NIHL.

Table 2.2 *NIHL cases by mine area*

Serial. no.	Area of the Mine	Number of NIHL Cases
1	Surface area of underground mine	24
2	Underground Mine	454
3	Strip Mine	53

4	Preparation Facility	105
5	Independent Shop	26
6	Office	2
7	Not Reported	1

Table 2.2 justifies the assumption that underground mining places are more noisy compare to other areas of the mine. The various reasons may include the confined area, lot of crowd within a limited time and use of high horsepower machinery etc. Thus there is more need for noise engineering control in underground mines.

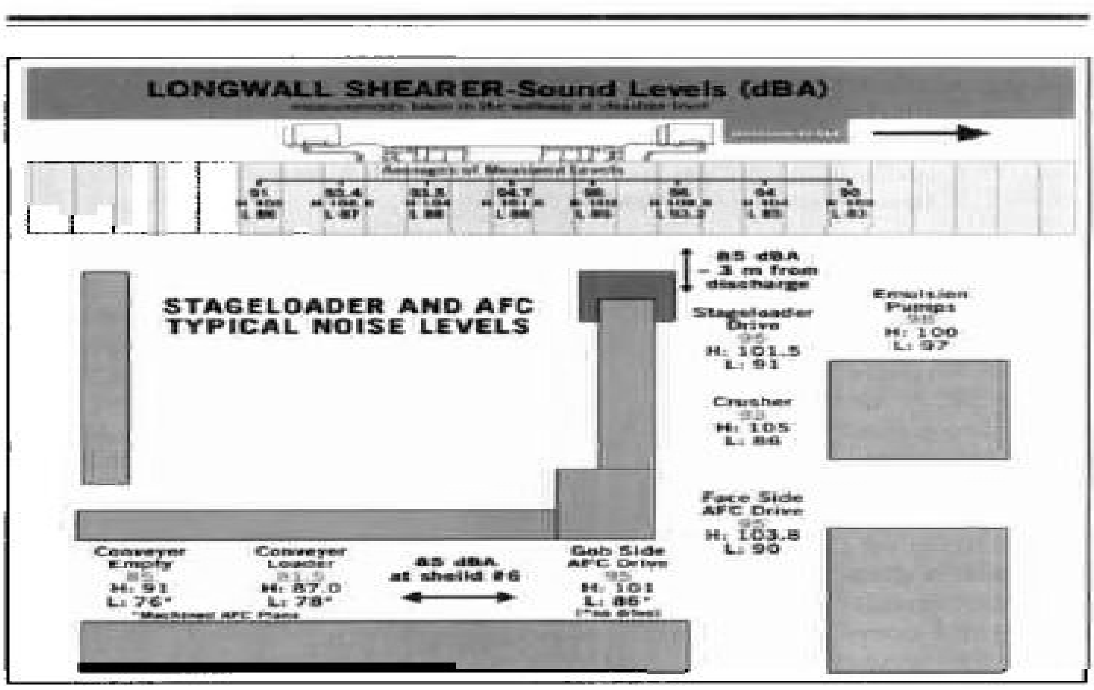
Valoski also did a study on technical feasibility of noise cancellation technology (NCT) [16]. He used NCT2000 in his experiments which were conducted under laboratory conditions. The internal switches were set to cancel the highest frequency of which it was capable. The NCT 2000 theoretically has an upper frequency limit 3000Hz. The noises were pure tones at the third octave band center frequencies between 80 to 1000 Hz. Although this work explained some broad field observations, it was very rudimentary in its approach. The beam theory equations used in the paper did not clearly explain the conditions reported for different orientations.

Frank's study [8] was a collaborative project of NIOSH and MSHA in the year 1996 that was designed to determine the prevalence of hearing loss among miners [12]. The report contained an analysis of 17260 audiograms for 2871 coal miners. ISO 1999 was followed to calculate and predict the amount of hearing loss observed for the miners.

Franks analysis showed that, by the time coal miner reaches the age of 50, 50% of them have hearing impairment. Thus NIHL is considered to be a major set beck for mining safety standard and high production goals.

Armour's research [1] in search of better hearing loss prevention program and to understand the source of noise underground did a noise study. He summarized the sources responsible for the longwall noise and also examined the technical controls at a mine. Using cycle events and area event, Armour inferred that there are three primary sources of noise: the chain, the drives, and the crusher. The cutting was major cause for the shearing machine noise. He also lists heat and maintenance as important factors to be considered. This work used dosimeter to get full shift time study. He used dosimeter event method and recorded separate events on a single dosimeter. He suggested two types of events recording: a cycle event and an area event.

Figure 2.5 shows detail SPL measurements taken from more than 30 longwall faces using the dosimeter event method. Figure 2.6 shows helmet which is Ridgeline's Pro-Ears system suppresses all noise above 85 dBA while simultaneously amplifying lower sounds, such as human conversation.



Average measured sound levels measurements were taken on more than 30 longwall faces using the dosimeter event method. The environmental noise levels are shown on the diagrams.

Fig 2.5 Longwall *face Sound Levels (dBA).*

Ridgeline's Pro-Ears system suppresses all noise above 85 dBA while simultaneously amplifying lower sounds, such as human conversation.

Fig 2.6 *Ridgeline's Pro-Ears system*

Chiang, Peng and Luo did a research on airborne dust distribution in Longwall mines and included dust survey for underground mines [7]. The reason to mention this piece of research is for its methodology. They have used some good ideas of surveying with concern with different part in longwall face. Attempt is made to get some of the surveying ideas from their work and make much better representation of noise survey.

Bauer and Babich [4] provided a study for what constitutes administrative controls for reducing workers noise exposure and also a qualitative explanation of the process of implementation and evaluation of an administrative control. He also summarized the main factors responsible for the noise exposure and they were: the type of task, workers location, noise concentration, SPL characteristics, and duration of exposure.

They conducted a study on various equipments used in the mines. They suggested that administrative controls should be based on the periods of exposure that results in largest dose. Figure 2.7 and fig 2.8 shows an example of cumulative dose plot for roof bolter operator and cell operator.

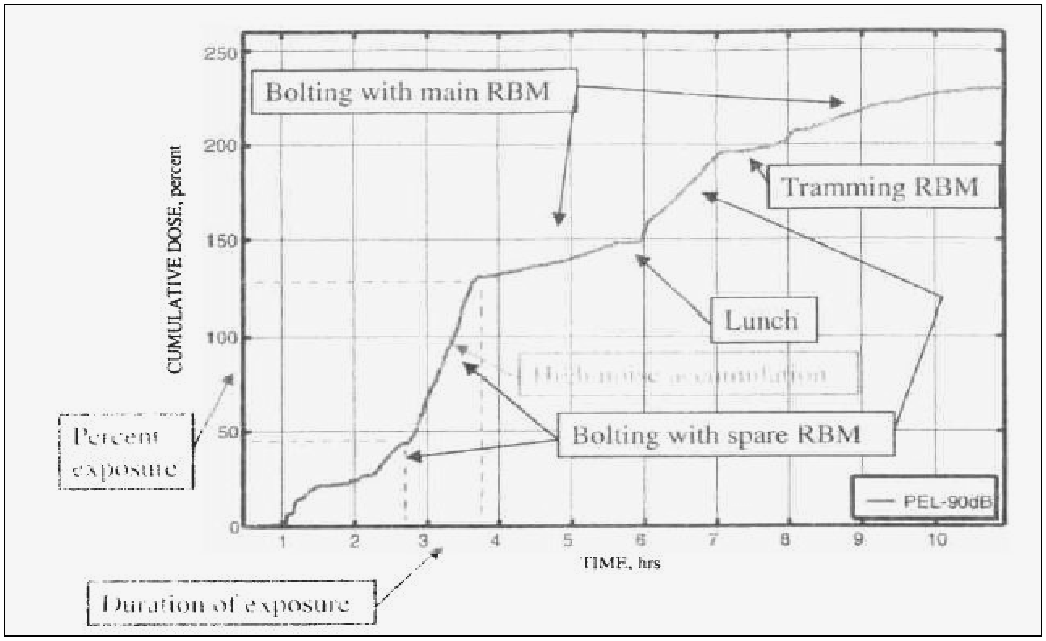


Fig 2.7 *Cumulative dose plot for roof bolter operator*

On the observation of his studies in the longwall mining sections, Bauer concluded that job switching/rotation, workers locations and equipment Operation can be the prime areas for effective administrative control.

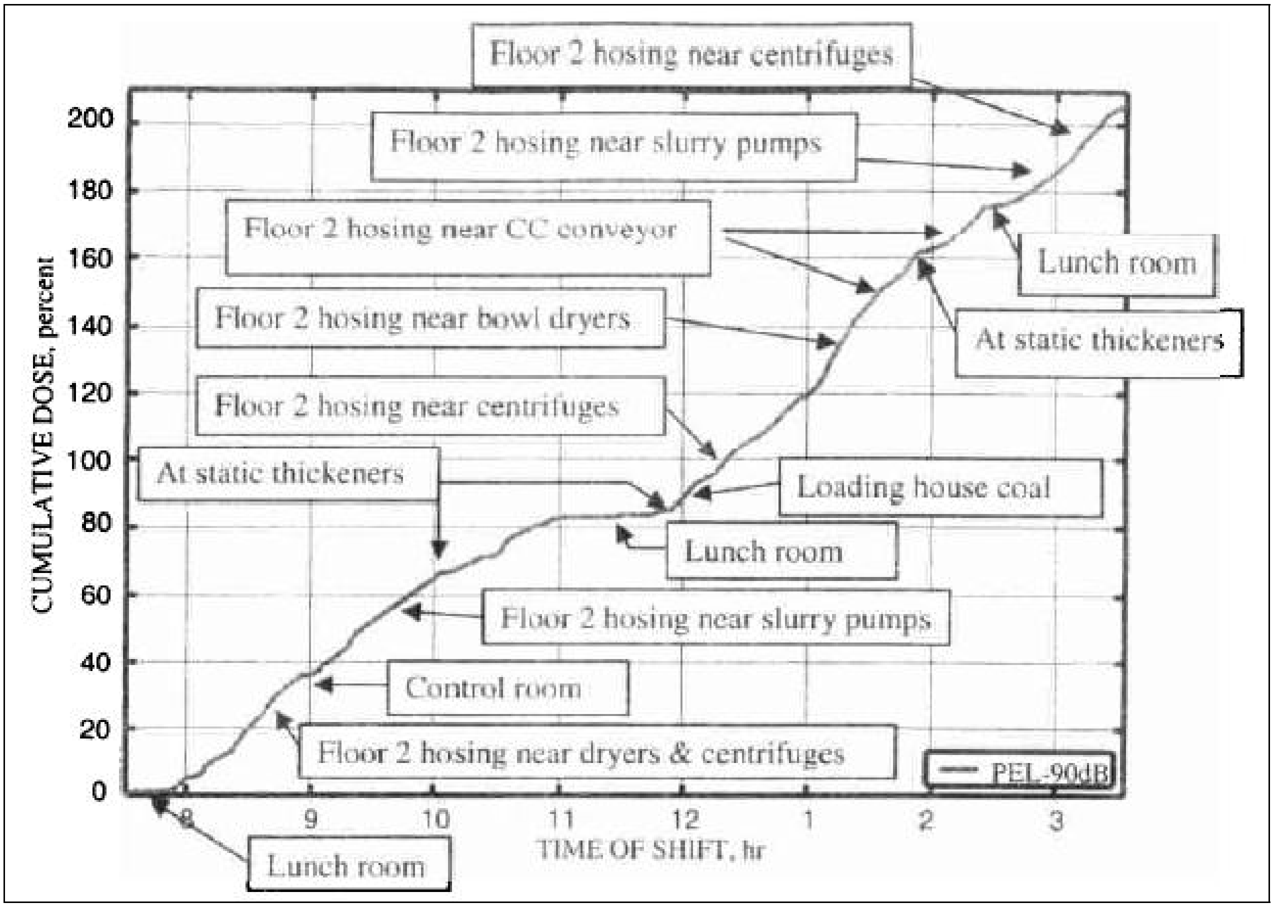


Fig 2.8 *Cumulative dose plot for cell operator*

This was a lucid method for task analysis and hence a proper selection of administrative measures can be adopted to avoid overexposure time for related tasks. The suggested remedial measures to deal with the NIHL include, change in time of exposure, passive noise control methods [4] and ultimately developing engineering controls e.g. active noise control technology.

Yantek of NIOSH's hearing loss prevention branch explained the study done by the group on continuous miner conveyors. (**American LONGWALL Magazine, May 2005 pp 5)**. Here a polyurethane coating was applied to the flight bars of a JOY continuous miner conveyor. A 7-8 dBA reduction was observed when SPL was measured in NIOSH's reverberation chamber. When measurement recorded in an underground coal mine near the tail section of the continuous miner the noise was reduced by 4-6 dBA when flight bars were coated with polyurethane material. The below figure 2.9 shows coated flight bars put to the test.

Coated flight bars put to the test.

Fig 2.9 Polyurethane coated flight bars

Hansen and Snyder [6, 15] also developed a system to engineer an ANC in the mining environment. The experiments done by them showed a significant reduction in the single tone frequencies and some of the lower frequencies. Also, Hansen did ANC experiments in a cabin of a mining vehicle. Figures 4 and fig 5 show the result for the experiment in the vehicle cabin. Though the work was inspiring but they failed to produce a good result for the random noise and high frequencies. He presented a relation about the wavelength and ANC work function. According to this research a frequency of certain dimension can only be canceled and above that the ANC become ineffective. More about this will be discussed in the 4th chapter.

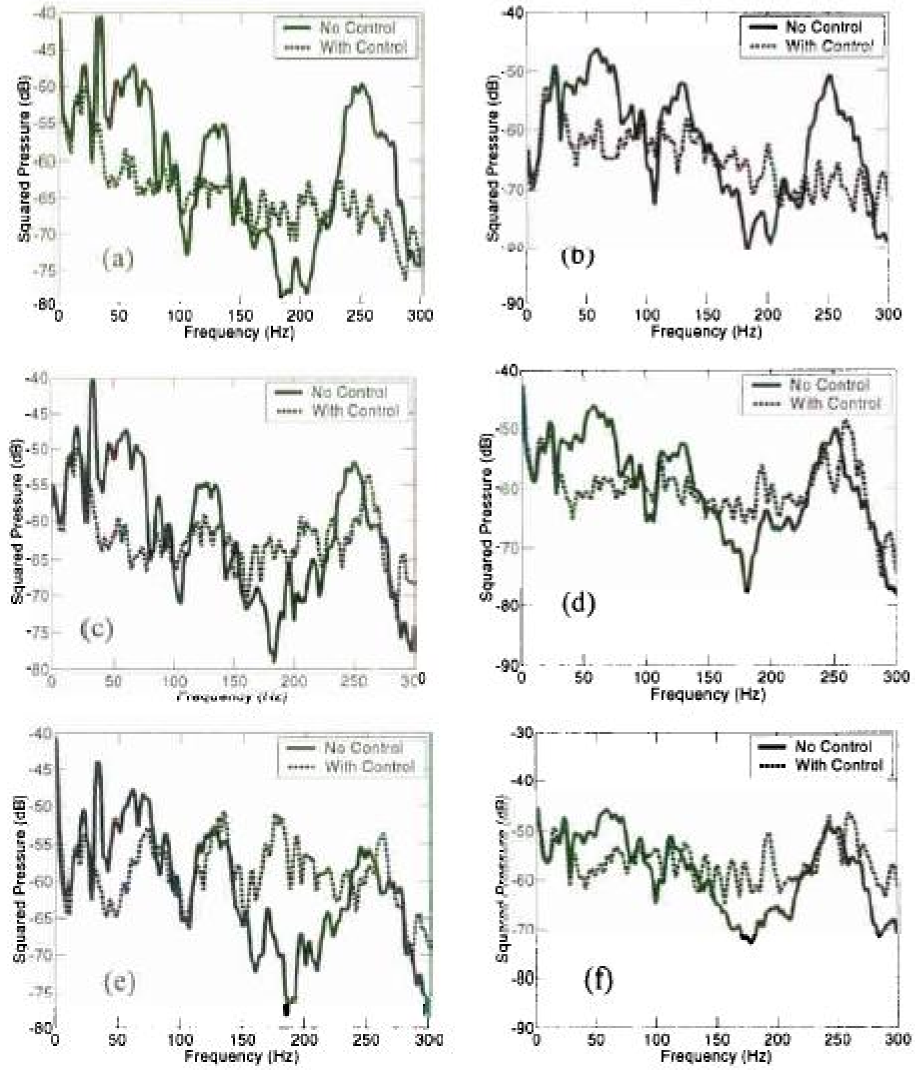


Figure 4. Real time ANC results for the mining vehicle cabin, showing sound pressure levels before and after control. Excitation consists of band limited random noise between 0 and 300 Hz. Figures (a), (c), and (e) show the results the sound pressure sensing strategy and Figures (b), (d) and (f) show the results for the energy density sensing strategy. Figure (a) shows the average of the sound pressure sensed by the 4 error microphones; Figure (b) shows the sound pressure sensed by the microphone located adjacent to the ED probe; Figures (c) and (d) show the sound pressure level averaged over the four monitor microphones within 300 mm of the furthest error sensor; and Figures (e) and (f) show the sound pressure level averaged over the four monitor microphones distributed throughout the cabin at a distance of at least 300 mm from the nearest error sensor.

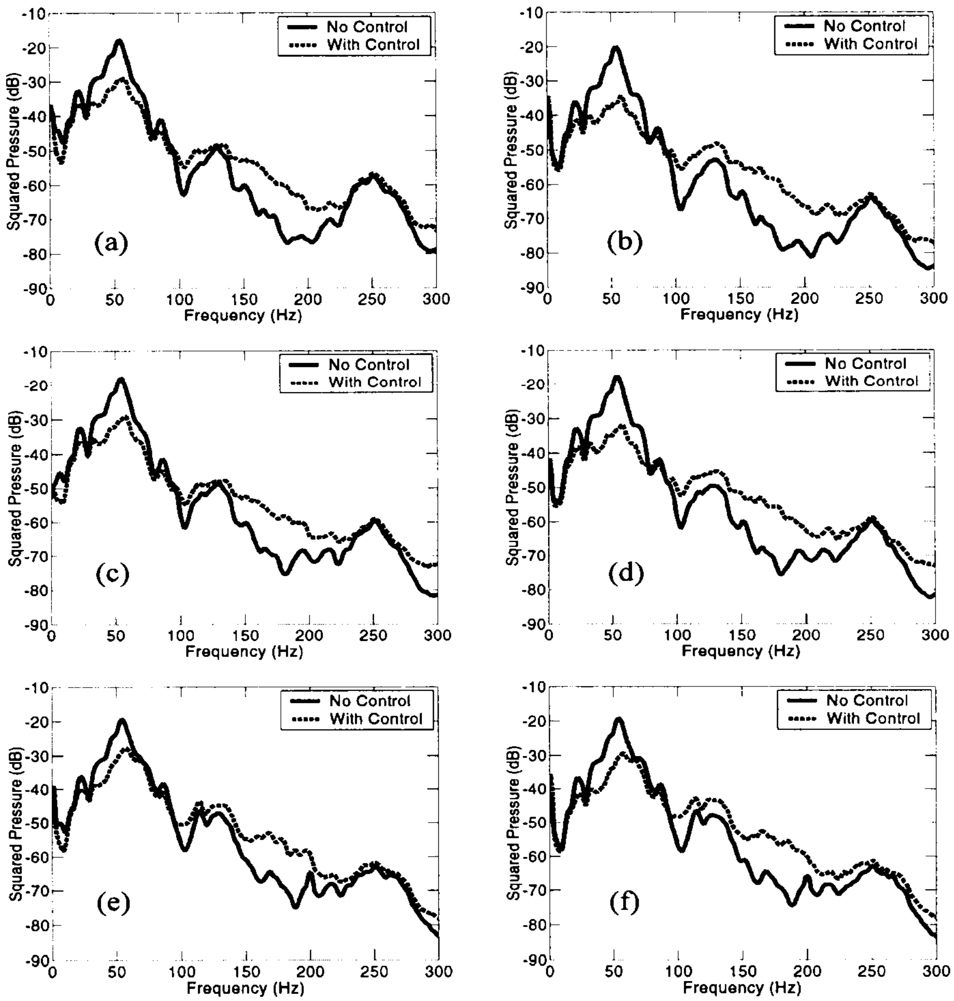


Figure 5. Real time ANC results for the mining vehicle cabin, showing sound pressure levels before and after control. Excitation consists of noise recorded in a mining vehicle cabin and band limited to 300 Hz. Figures (a), (c), and (e) show the results the sound pressure sensing strategy and Figures (b), (d) and (f) show the results for the energy density sensing strategy. Figure (a) shows the average of the sound pressure sensed by the 4 error microphones; Figure (b) shows the sound pressure sensed by the microphone located adjacent to the ED probe; Figures (c) and (d) show the sound pressure level averaged over the four monitor microphones within 300 mm of the furthest error sensor; and Figures (e) and (f) show the sound pressure level averaged over the four monitor microphones distributed throughout the cabin at a distance of at least 300 mm from the nearest error sensor.

2.4 Closing Remarks on Literature Review

After analyzing the past works in this chapter, the following important points emerge:

- Most of these works followed the traditional method of data collection.
- Very few researchers tried to cover the frequency analysis at the various locations.
- Examining the magnitude and nature of noise in the underground mining makes it difficult to correlate sound source and its propagation pattern. Hence the key factor that determines actual SPL is Octave band analysis. Also Sound Power Level to calculate more accurate noise levels..
- For active noise cancellation (ANC) technology, the range of low frequency values of overall SPL and their contribution must be found in field measurements. As different combinations can be obtained in the ANC set up, as many combinations as possible must be considered in the ANC set up.

CHAPTER

3 NOISE SURVEY AND CHARACTERIZATION OF NOISE FIELDS

3.1 Introduction

This chapter mainly discusses the noise surveys undertaken for this research to characterize and map the noise in and around longwall faces. The noise behavior is very complex and the noise field which is reverberant in the case of underground mining makes the issue more complex to analyze. Every effort is made to get and use latest available sophisticated gadgets in the measurement and analysis procedures. Also, MSHA has published new noise standards for mining (Federal register, 1999). The new law came into force from Sep.13, 2000. It adopted provision similar to U.S. Occupational Safety and Health Administration's (OSHA) hearing conservation amendments. The added requirements of the regulations are a permissible exposure level (PEL) of 90 dBA time weighted average for 8 hours (TWA8). No credit is allowed for the use of personal hearing protection, feasible use of engineering and administrative controls for noise exposure reduction are encouraged. Survey was performed with compliance of new MSHA regulation.

In this chapter also the important assumptions and conditions under which the results of the work are valid will be outlined in a lucid pattern. The major purpose of the current work is related to the effect of mine confinement and set-up on the properties of noise produced. The survey work will be explored and compared to the available database, if any. The interpretation from the noise characterization will be used as basic criteria for the purpose of design of active noise control technology (ANC). Hence, in-depth discussions of possible data analysis are covered in this chapter.

3.2 Noise in Mining Industry

The layout of underground mines shows that it is confined with limited option of space, the area is full of uneven surface and huge level of mechanization is employed to achieve high production. Among the working places in underground mining the Longwall mining faces could be noisier than other locations due to the use of heavy and energy-extensive machines in the rock breakage (cutting and crushing) and the haulage operations in the confined area. The typical setup in a longwall has chain conveyor, shearers, stage loader etc. The horse power energy consumed is high compare to normal operations.

The characteristics of noise are very important factors responsible for the overall noise control process. The noise could be monotone or single tone comprising of one frequency and hence easier to process and control. But due mining conditions the noise produced is random noise. It consists of frequencies ranging from 20 Hz to 20 kHz. These frequencies are produced at different level at every point making the analyzing part more difficult. According to the theory of the noise, the directivity and reverberation interact with each other.

Mine Safety and Health Administration (MSHA) has published new health standards for occupational noise exposure (Federal Register, 1999) and it's effective from September 13, 2000. One of the significant changes is that every miner must be enrolled in a hearing conservation program (HCP) if his full-shift noise exposure is at or above the action level of 85 dBA TWA (8 hr) or 50% dose. Also, under the new regulation Permissible Exposure Level (PEL) of 90 dBA TWA (8 hr) is included and no credit is considered for use of personal hearing protection (PHP), and the primacy of engineering and administrative controls for noise exposure reduction [1, 9].

From the Noise measurements taken in the US coal mines, the following points are worth noting:

- Need for more intense and regular noise database for all mines.

- Data indicates higher lower frequencies are dominant frequencies. This trend is apparent for almost all machinery used in the mines.
- If possible new designs parameter should be selected at the manufacturing stage for different mine machinery.

3.2.1 Works Performed

This is one important theoretical part to know about sound. To make sure before going to survey what may be different situation for noise survey outlined. There are three types of sound fields i.e. near field, far or free field and the reverberant field. The below figure 3.1 explains:

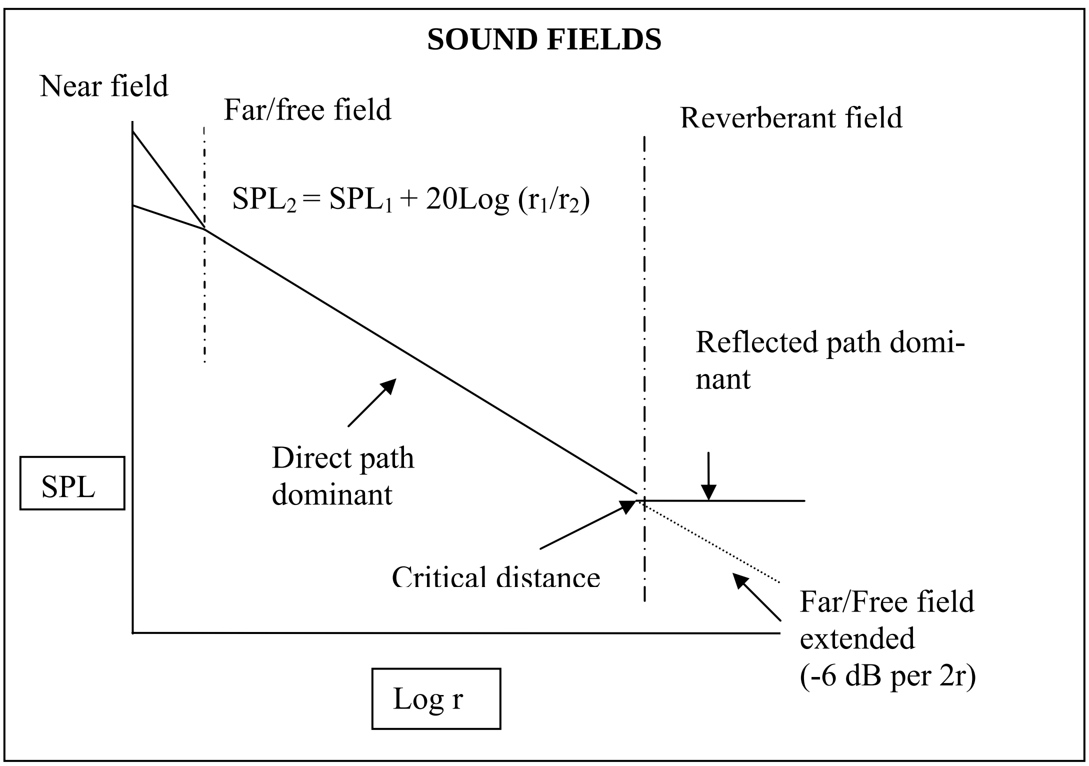


Fig.3.1 *Sound fields*

The far field is defined as the area in which sound waves propagates uniformly from the source usually in space unencumbered by obstructions and reflections. The theoretical formula derived works very well in this area, where simply by conversion of energy as the

wavefront in all directions SPL at a point can be estimated. SPL decrease by 6 dB by doubling of distance.
The near field is observed in the area close to the source, generally one wavelength distance of the dominant frequency and the wavefront still adjusting. Due to the unstable wavefront near field is unpredictable and may not follow the theoretical formula of far or free field. The reverberant field is the region where the reflected noise is close enough to the direct path noise and adds the reflected wave to overall SPL. Sorting accurate sound field is one of the important parameters for selection of effective noise controls.

3.3 Proposed Work

The noise pattern underground is very unpredictable and no known methods are available to accurately predict them without field measurements or observations.
Generally noise survey used to record the overall SPL and perform OBA analysis as per need; assumptions are also made about the reflection and other underground parameters like temperature, humidity, and dust etc components effect on the noise.

3.3.1 Field Noise Surveys

The standard operating procedure for noise survey was outlined. It included both on the proper instrument calibration and noise measurement techniques. Instrument handling and data collection were performed as per the industrial standards. From the previous experiences of various researchers a format of noise recording table was outlined and hence used in the field surveys. Longwall coal mine is a different world in itself. All the different possible variation in the survey was studied and proper arrangement was made. Hence, it is important to consider the variation of number of parameters to achieve and stimulates practical noise environments from the measurements.

Following are the range of instruments used in the noise survey:

1) Quest Technologies, Sound Level Meter (SLM), 2900.

2) Quest Technologies, 1/3, 1/1 Octave Band Analyzer (OB300).
3) RCX-220 Digital Noise Recorder.
4) Digital Watch.

As mentioned above standard noise survey instruments were calibrated and used. The equipments used during the noise survey are shown in fig 3.2. They are noise logging dosimeter, RCX-220 digital recorder and sound level meter with calibrator (L to R).

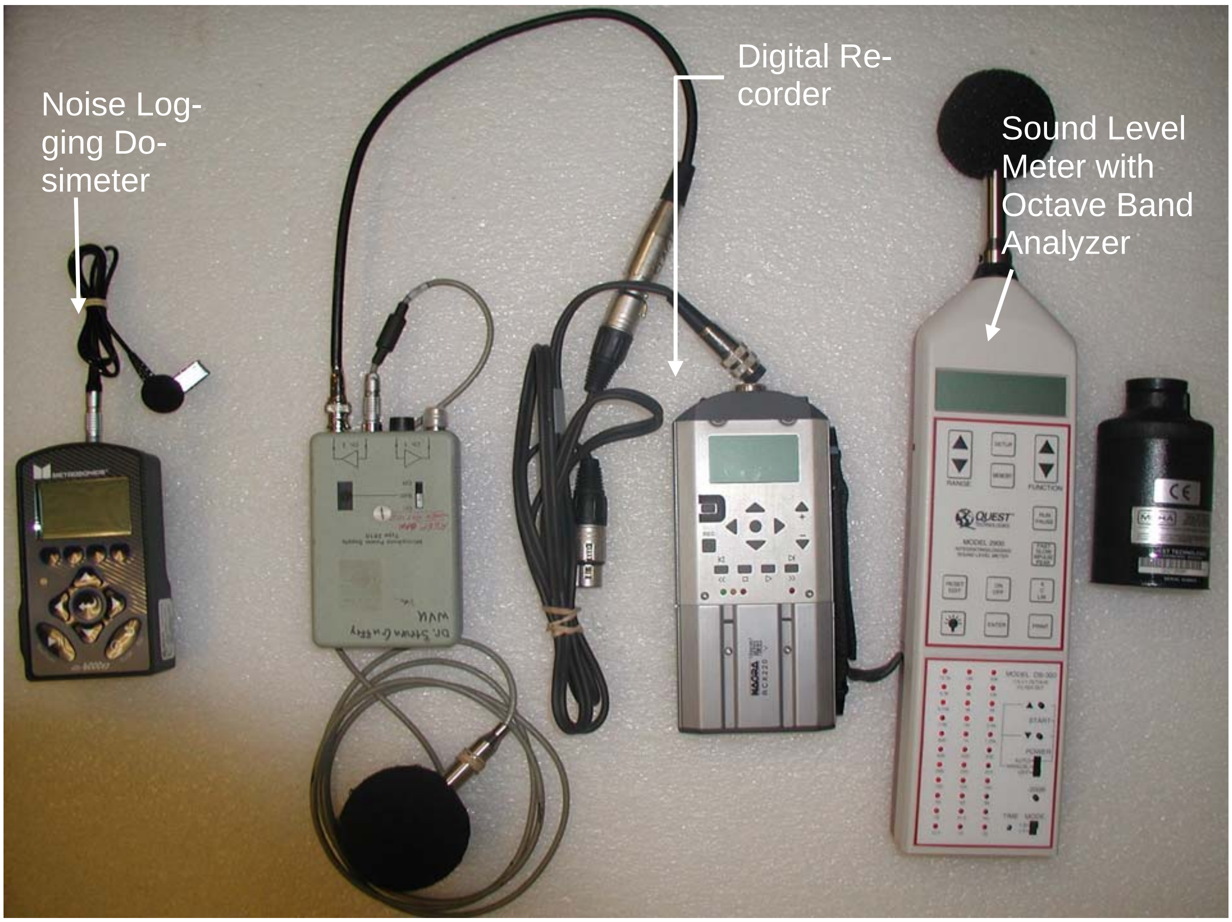


Fig 3.2 *Noise Survey Equipment*

Noise survey was performed in different stages. In the first stage the SLM was used to record the noise at the various positions in and around the longwall face. The survey results are used to plot the profile of SPL in the area. The second stage was to perform 1/3 octave band analysis (OBA) at various points of interest in the face. The OBA analysis helped to collect data for spectral analysis of the acoustic energy distribution in the possible frequency range. To cover the noise exposure by task analysis dosimeter was used to record minute by minute SPL. Source exposure time was recorded so that estimate of dose can be calculated.

- 5 sets of dosimeter were used at different points.
- RCX220 was used to record noise at various points and then analyze data with the help of OROS NV-GATE analyzer.
- Stage Loader was picked as the prime target for noise survey.

Noise surveys have been conducted in two longwall mines that conduct their mining operations in the Pittsburgh coal seam with mining height ranging from 6.5 to 7.0 ft. One mine is located in northern West Virginia and another in eastern Ohio. The two mines had the same types of shearers and shields but with different stage loaders. The surveys include the noise exposure dosage for different machine operators, the sound pressure level (SPL) distribution around a number of mining machines, and the SLP and frequency relationship at the selected machines. The octave band data (SPL vs. frequency) are especially useful for the design of engineering noise controls. To accomplish the task, noise readings were taken distances from the source.

3.3.2 Noise Survey at Mine A

The figure 3.3 bellows shows a setup in a longwall face. The coal at the face is cut by the shearer loader. The shearer loaders are set on the panline of an armored face conveyor (AFC), which is liad on the floor parallel to the faceline. Self-contained motor is used to move shearer loader by means of a winch running along a static chain whose ends are anchored at the ends of the face or at the drive units of the AFC. Shearer loader has single or double drum mounted on the face side. The rotating torque available at the axis of the drum is used as the cutting force. Coal is loaded onto AFC and transported to headentry T-junction and then coal is dumped onto a stage loader, which in turn empties to the entry belt conveyor.

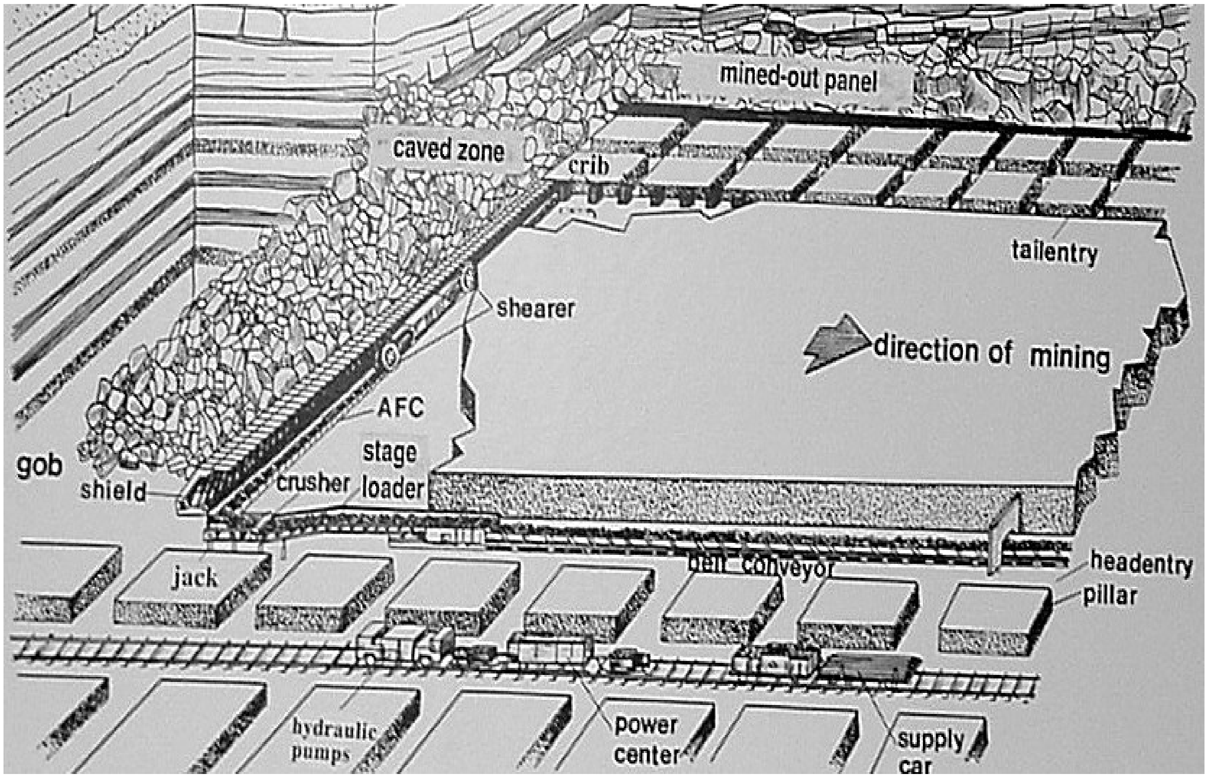


Fig 3.3 *Typical longwall retreating panel layout (Syd S Peng., Longwall Mining)*

A longwall mining face area has energy intensive mining machines like shearer loader, AFC and stage loader. All these machines are placed within a confined and congested space. It is most likely due to many surface convolutions on the side walls, the roof and the floor; sound waves are diffusely reflected. The distributions of the A-weighted sound pressure levels along the crusher/stage loader (about 49 m long) in longwall face from two surveys are shown in Fig. 3.4 Both surveys show the similar distributions indicating that the sound field at this machine would not vary significantly. The locations along this machine with high noise levels are close to the openings at both ends where the coal enters and leaves the machine. The peak sound level around the tailpiece end ranged from 98 to 104 dB. A zone where the noise level is much lower than 90 dB is located in the central portion of the machine.

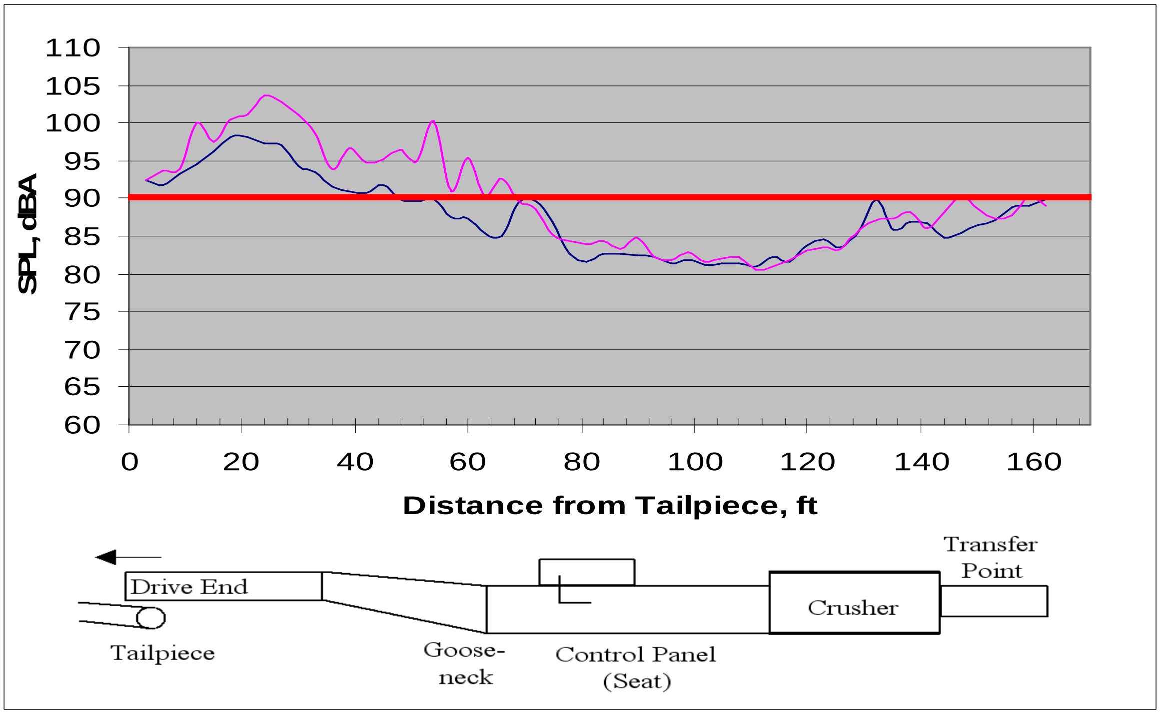


Fig. 3.4 *Noise Level at Different section of a Stage Loader*

Hence measured sound pressure level (SPL) distributions along the stage loader suggested following points:

- Similar SPL distribution patterns
- Higher noise levels near both ends of the machine, especially on the tailpiece side
- A low noise zone in the central portion of the machine.

The contribution to noise dose from the various tasks of the headgate operator during the survey is shown in Figure 3.5. It shows that the headgate operator would be exposed to a sound pressure level between 90 dB and 98 dB in the normal operation time. Occasionally, when the longwall face was not producing coal but the AFC, crusher and the stage loader were still running empty, the noise level in and near the headgate T-junction would be very high. Figure 3.5 shows the sound pressure level could peak at 105 dB in such situation.

However, such situation would be relatively short and would not contribute significantly to the cumulative noise dose to the operator.

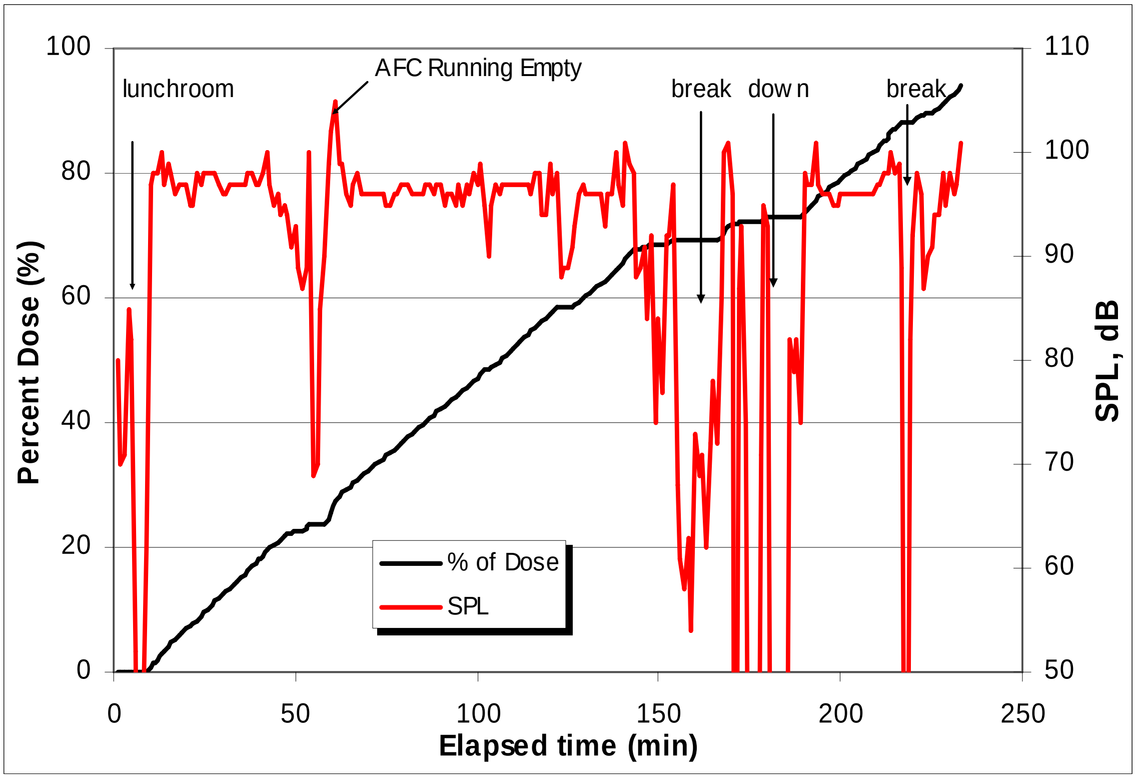


Fig. 3.5 *Noise exposure dose for headgate operator at the short stage loader*

A typical dose accumulation for the shearer operators is given in Fig. 3.6. It shows during the coal cutting operations, the shearer operators were exposed to a noise level between 90 and 100 dB. The duration, average sound pressure level and the cumulative noise dose at different activities for the tail shearer operator are summarized in Table 3.1. Both Fig. 3.6 and Table 3.1 show that the main sources of the noise dose were the coal cutting.

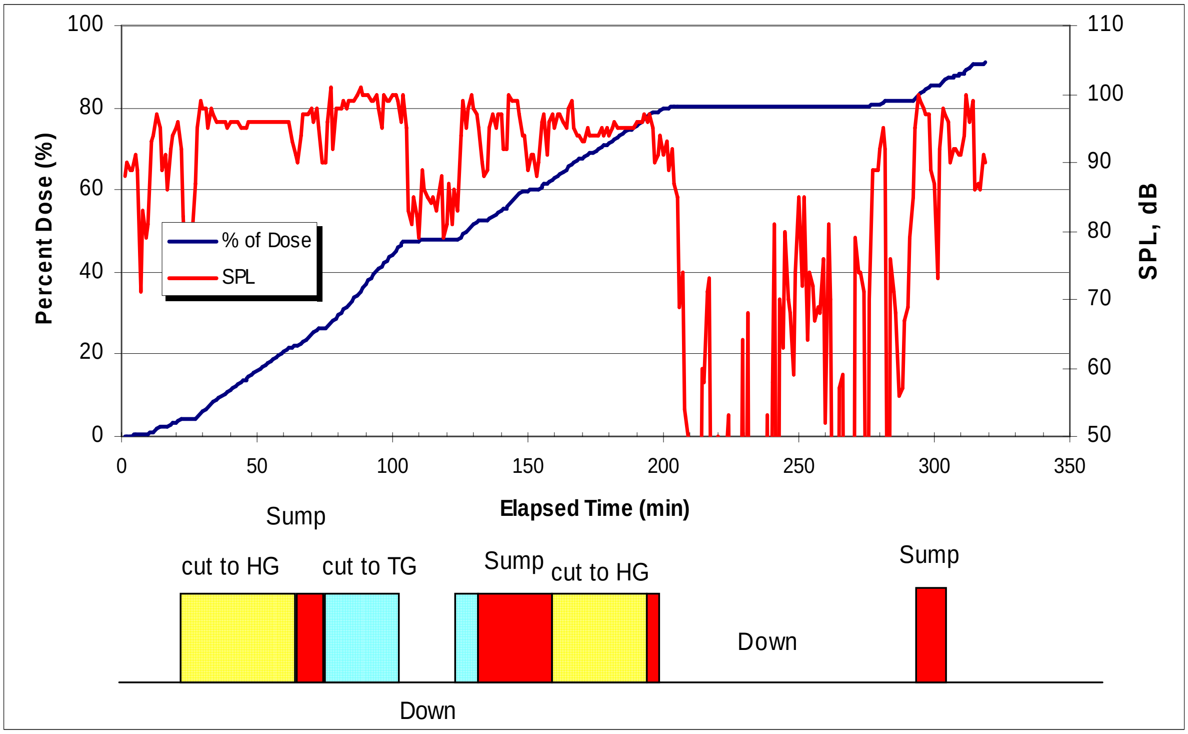


Fig. 3.6 *Noise exposure dose for tailgate shearer operator*

Table 3.1 *Dose contribution and SPL by Activities for tailgate shearer operator*

Mining Activities	Duration min.	Average SPL dBA	Sum of Dose %
Control Panel	8	84.6	0.8
Shut Down	122	79.6	6.0
AFC Run Empty	11	85.3	1.2
Cutting to HG	69	95.7	31.6
Cutting to TG	34	98.6	23.3
Sumping @ HG	38	94.6	15.0
Sumping @ TG	37	93.8	13.0

Figure 3.7 shows the results of the octave band analysis of the noise surveys at different locations along the stage loader. It reveals that the frequency distribution of the promi-

nent sound pressure levels occurred within the 20 to 2,000 Hz range at the location of the tailpiece (exit end). At the other locations, the dominant frequencies are narrowed to between 20 and 1,000 Hz. The underground surveys also found that the range from 100 Hz to 650 Hz is consistently the dominant noise frequencies in the longwall faces.

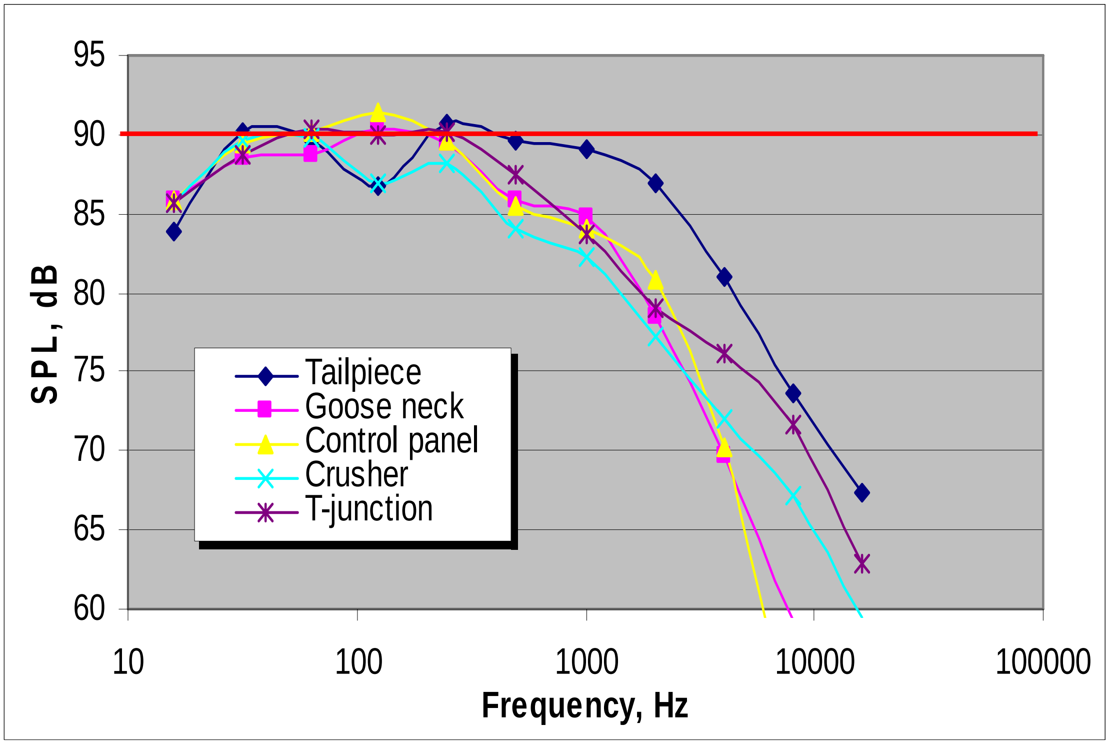


Fig 3.7 Results of octave analysis of the noise field along the stage loader

Summary for octave band analysis for stage loader noise:

- There was significant overall noise.
- The different sections of the stage loader had different noise level.
- The frequency distributions were very significantly related to overall SPL.
- The behavior of lower frequencies was dominant. The dominant frequencies in the longwall faces: 100 - 650 Hz.

The dosimeters were set at a criteria level of the 90 dBA permissible exposure limit (PEL) with 5 dB exchange rate and 90 dBA threshold cutoff. The estimated dose for full shift (8-hour) was calculated. Also, proper care was taken to record minute by minute position and activities of the workers wearing dosimeters. This helped the data to correlate the noise sources they were exposed to sound pressure level and octave band measurements made of those activities and sources.

3.2.3 Noise Survey at Mine B

A comprehensive set of noise surveys were conducted in the mine B. This survey was more intense and focused on the following two objectives:

(1) To identify the mining machines, causes and operating conditions that produces the noises,

(2) To collect data for spectrum analysis – acoustic energy distribution in the possible frequency range for proper selection of noise control measures.

To analyze the task contribution to overall noise dosimeter were matched with timing and positions of the particular noisy sections. Details pertaining to the survey and points selected are provided later in this chapter. For purpose of the current work, the survey is divided in two steps, first include the SPL data and the other include the 1/3 OBA at various sections of the mine. The length of the stage loader was 80 ft as compare to stage loader of mine A, which was 140 ft. The survey output was analyzed and interpreted.

The figure 3.8 presents two sets of SPL data along the length of the stage loader. Similar SPL distribution pattern was observed.

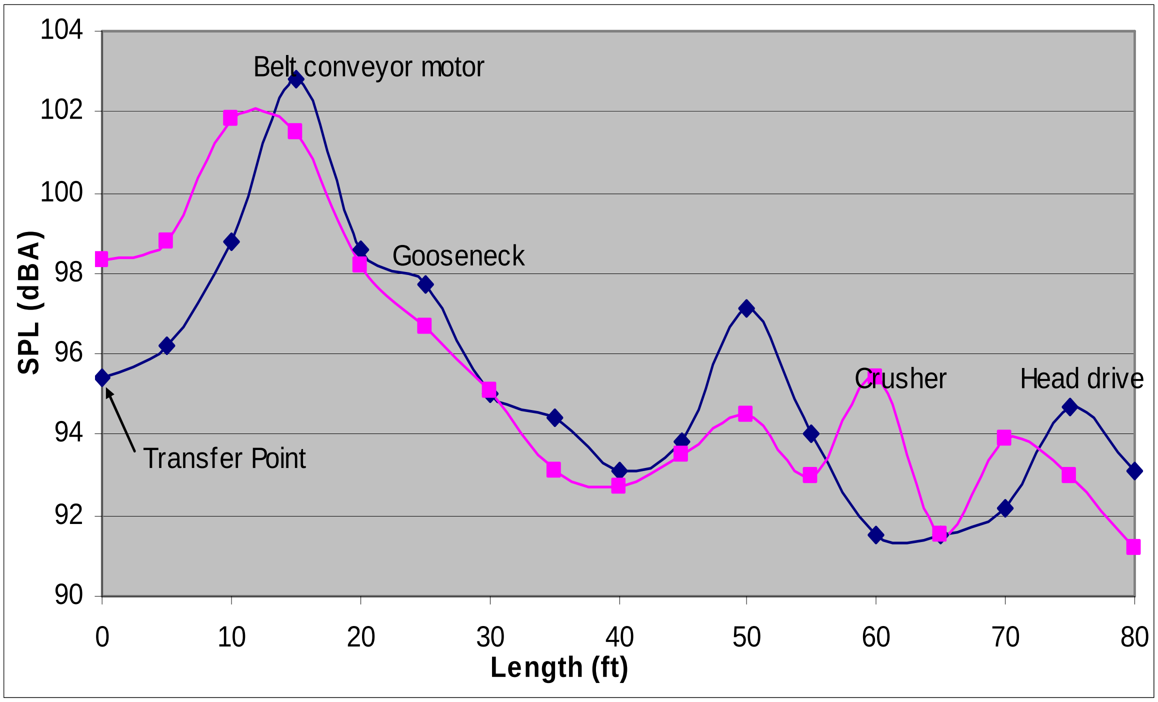


Figure 3.8. *Overall SPL aligned with Length of the Stage Loader*

The Motor section SPL ranges from 98 dBA to 102 dBA. Goose neck ranges anywhere from 94 to 98 dBA. Crushes section contributes 91 to 94 dBA noise level in the Longwall section. Head drive part of stage loader has 91 to 93 dBA noise level. It was also observed that higher noise levels were present at the end of the machine, especially belt drive motor on the tail piece side and the gooseneck. The central portion of the stage loader experienced a low noise zone. Since these certain locations are the highest noise sources, octave band analysis was focused on these locations. The brief discussion of OBA data is presented in the OBA section later in this chapter.

In the case of noise in the entry and its propagation, an attempt was made to record noise with respect to the distance away from the transfer point from the stage loader. Figure 3.9 reveals the natural phenomenon that noise dies as it moves away from the source i.e. stage loader. This figure also shows that the SPL values of the individual components of the mine entry will be different. In this 200 ft noise survey section, the lowest value is 82 dBA and the highest is 103 dBA. The range of difference is 20dBA, which is significantly high.

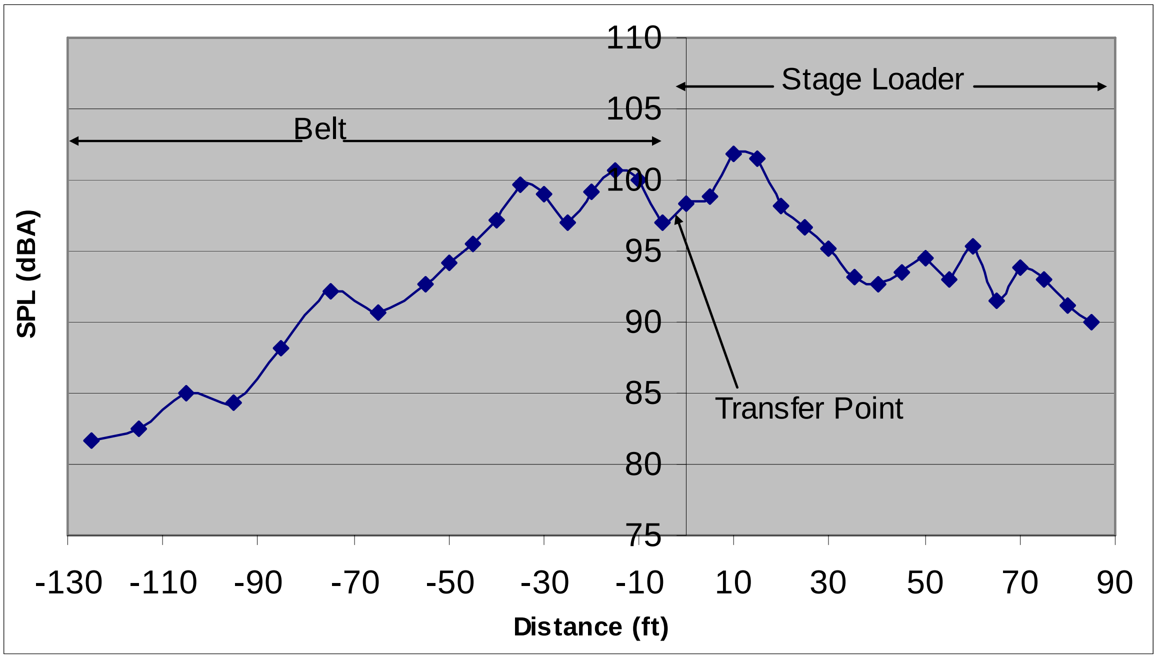


Fig 3.9 *SPL along the Stage Loader Section*

Noise Survey in the crosscut:

The noise survey was carried out in the last open crosscut panel and in the track entry. The survey was divided into two sections in the last open crosscut (A) and in the track entry (B) as shown below in the Fig 3.10. The A section covered the full length of the crosscut. Sound level meters were used to measure the overall SPL and also octave band analysis was done at various points of the sections A and B respectively.

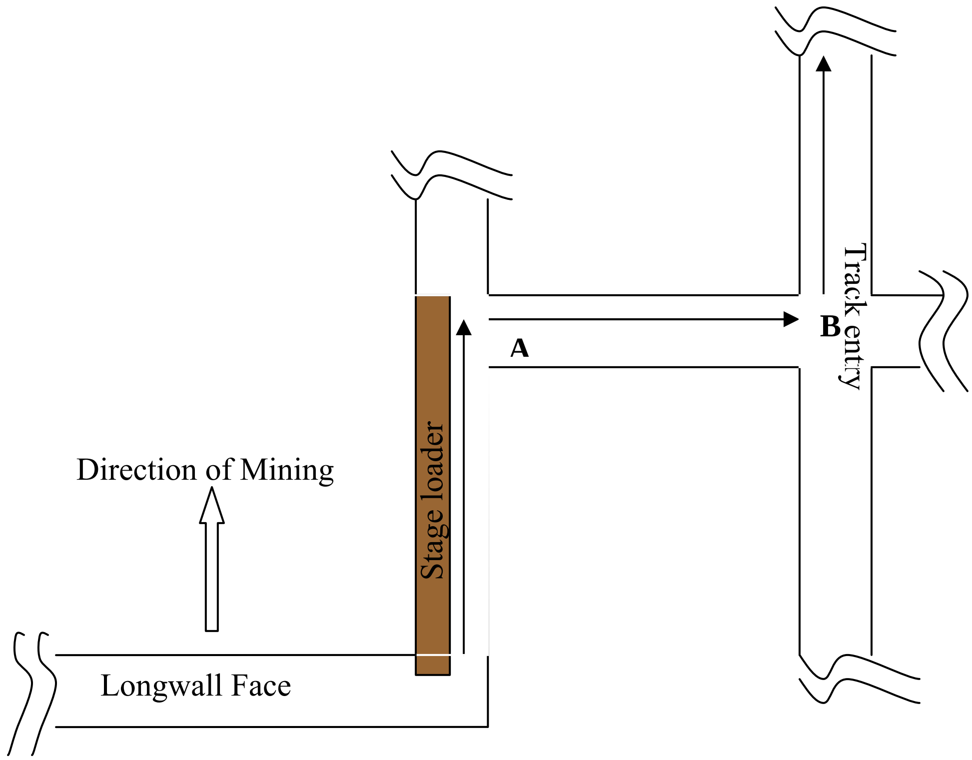


Figure 3.8. *Overall SPL aligned with Length of the Stage Loader*

Table 3.2 shows the SPL values in the entry; it ranges from 77 dBA to 96 dBA in the section A and 61 to 76 dBA in the section B of the survey.

Table 3.2 *Cross Cut Noise Survey*

Position	Length(ft)	SPL(dBA)	Position	Length(ft)	SPL(dBA)
A	5	95	B	10	76.2
A	10	96.2	B	20	75.7
A	15	90.6	B	30	71.9
A	20	90.4	B	40	70
A	25	87.4	B	50	68.1
A	30	87.5	B	60	66.6
A	35	86.2	B	70	64.2
A	40	83.1	B	80	64.1
A	45	77.6	B	90	63.3
Edge of Pillar	50	78.4	B	100	63
Center of Truck Entry	60	76.8	B	110	61.4
			Center of next cross cut	120	59.2

However the noise survey on the longwall face revealed a different picture. The SLM was used to measure overall SPL with respect to the shield numbers. Also, minute by minute data was recorded using dosimeter at various points. Some points were also used for octave band analysis.

Figures 3.11 represent the SPL level changes at various shield locations when the shearer was not nearby. The two sets of data almost show similar pattern.

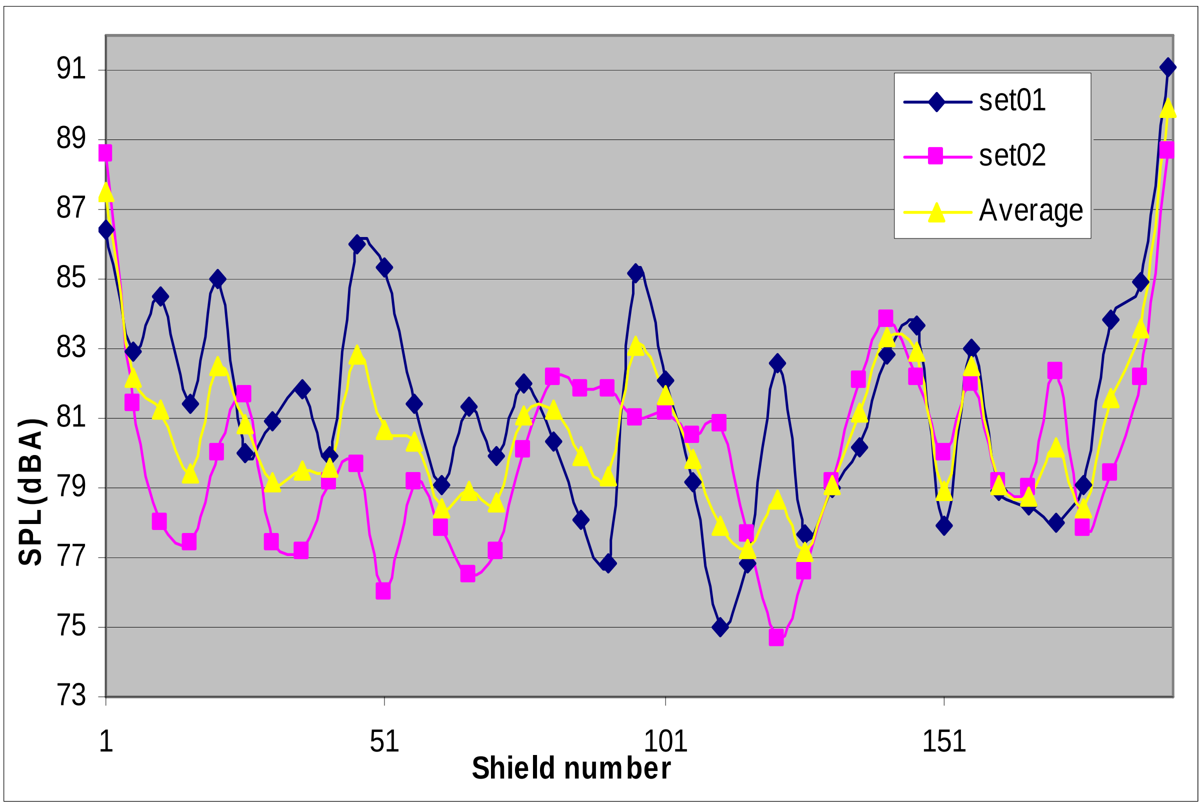


Figure 3.11 *SPL at the Longwall Face with respect to Shield Number.*

Octave Band Analysis:

The next step was octave band analysis of the noise present in the various sections of the longwall section. The OBA analysis provides details about the frequency spectrum and helps in determining the dominating frequency band. Table 3.3 provides the details about the $1/3^{rd}$ OBA analysis at various section of the stage loader. The stage loader is 60 ft long with actual of 57 ft long enclosure.

Table 3.3. *Octave Band Analysis at the Stage Loader*

	Tail piece	**Tail Motor**	**Goose neck**	**Control panel**	**Enclosure entrance**
	0 ft		30 ft	45 ft	60 ft
dBA	94.4	102.8	98.2	93.7	92.5
dBLin	99	105.5	105.7	103	101.6
Freq. (Hz)	**SPL, (dB)**	**SPL, (dB)**	**SPL, (dB)**	**SPL, (dB)**	**SPL, (dB)**
16	85.7	92.5	91.5	95	91.4
31.5	90.6	98.8	97.2	96.6	92.7
63	93.3	96.9	94.7	94	92.3
125	96.3	96.3	95.2	97.7	96.6
250	92.5	99.3	93	93.7	92.1
500	92.3	102.3	93.3	95	91.8
1000	94.8	97	90	91	87.2
2000	87.8	96.6	86	87.6	84
4000	81.9	93.6	77.6	77	78.6
8000	74.5	80	68	66.9	68.4
16000	67.5	65.9	54.3	55.1	61.4

Though all the sections are noisy within those tail motor sections shows 102 dBA, Gooseneck produces 98 dBA and etc. In all the noise sources the dominance of lower frequency can be easily understood by observing Table 3.3.

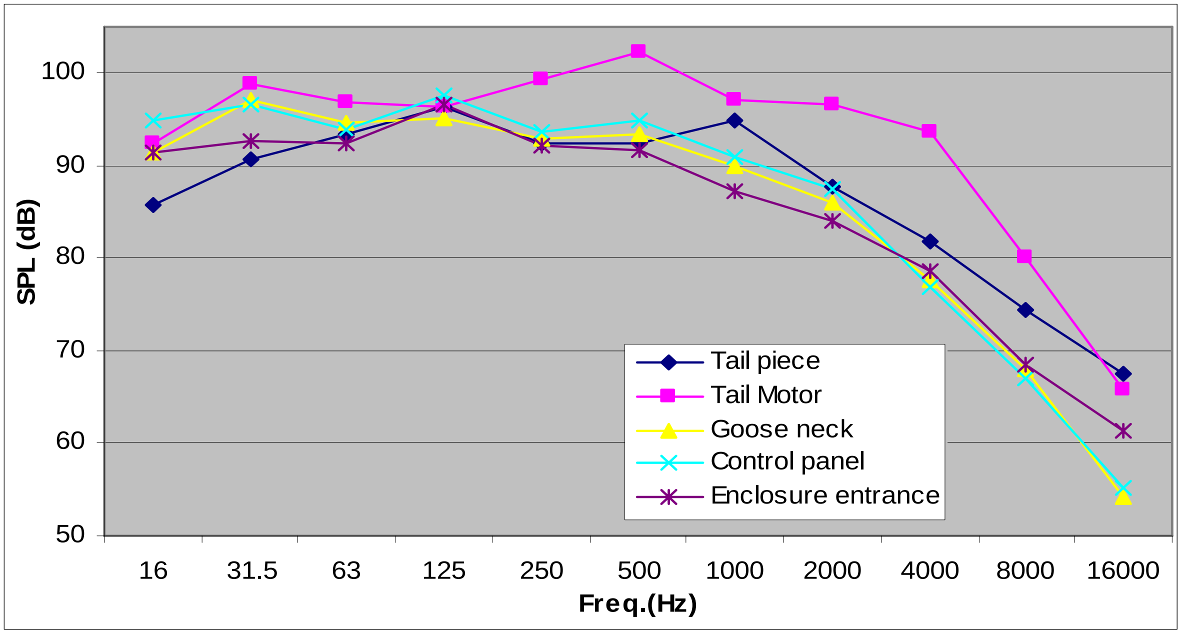


Figure 3.12. OBA along the Stage Loader at Mine B

In the case of noise around longwall stage loader, the importance of low frequencies is understood and clearly demonstrated by figure 3.12. The analysis revealed that the frequency distribution of the prominent sound pressure levels occurred within the 0 to 2000 Hz range. It was also found that the 125Hz to 1000Hz are consistently dominant frequencies.

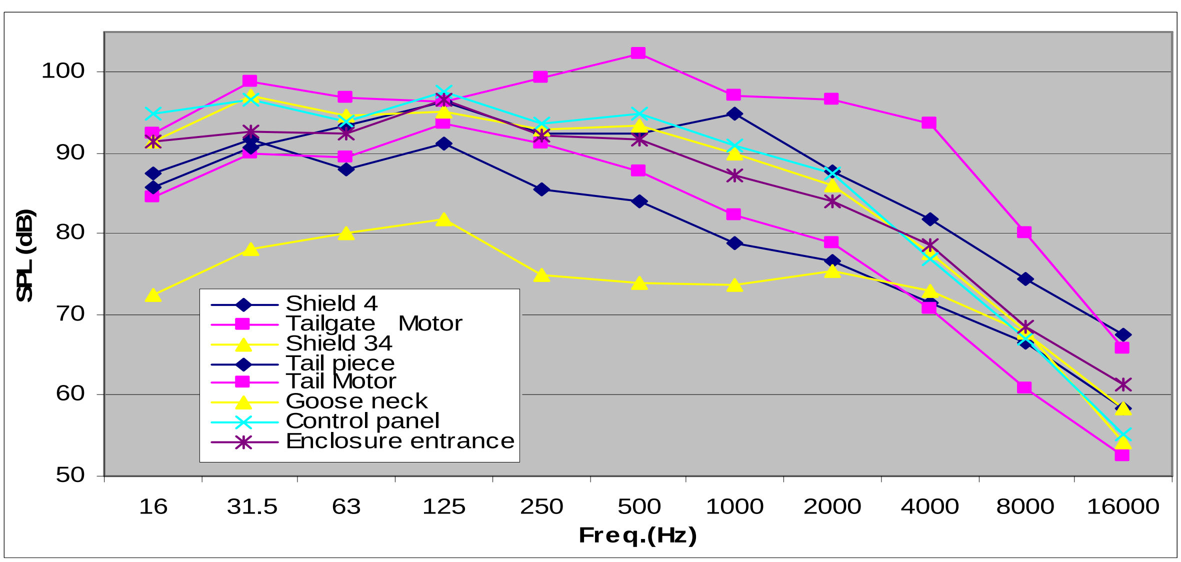


Figure 3.13 OBA along the Stage Loader at Mine B

The octave band analysis of the frequency spectrum showed that the tail motor, tail piece, goose neck, control panel and the crusher section in the stage loader are dominated by high low frequency noise. All of them demonstrated similar pattern (fig 3.13).

Table 3.4 OBA at the Headgate

	Shield 4	Tailgate Motor	Shield 34
dBA	83.6	87.6	79
dBLin	99.2	97.4	87.1
Freq (Hz)	**SPL (dB)**	**SPL (dB)**	**SPL (dB)**
16	87.4	84.6	72.4
31.5	91.7	90	78.2
63	87.9	89.4	80.1
125	91.1	93.7	81.8
250	85.6	91.3	75
500	84.1	87.7	74
1000	78.8	82.4	73.6
2000	76.6	78.8	75.4
4000	71.5	70.6	72.9
8000	66.5	60.9	67.7
16000	58.5	52.4	58.4

The OBA at the headgate showed an overall SPL of 83.6 dBA at shield no.4, 87.6 dBA at tailgate motor and 79 dBA at Shield no.34. A similar pattern of lower frequency dominance was observed at all of them (Table 3.4).

<u>Octave Band Analysis at the Power Pack Unit:</u>

Continuing the idea to characterize the mine noise, frequency analysis was performed on the power pack unit section. Table 3.5 shows that the overall noise at the compressor was 96 dBA and pumps produced a noise level of 100 dBA.

Table 3.5 *OBA at Power Pack Unit.*

	Compressor	Pumps	at - 60ft

dBA	96	100.2	82
dBLIN	98.7	103.7	93
Freq.(Hz)	SPL (dB)	SPL (dB)	SPL (dB)
16	77.2	83.7	79.1
31.5	87.3	97.7	88.9
63	89.7	88.2	81.5
125	91.7	94.2	84.6
250	89.4	95.4	80.5
500	94.1	100.8	73.4
1000	90.8	96.8	71.2
2000	88.4	90.1	60.7
4000	86.5	83.6	52.2
8000	78.7	79.4	51.6
16000	73.1	69.9	41.6

Figure 3.14 shows that the overall noise at the compressor was high. The pumps which produced a noise level of 100 dBA showed a considerably high value for the lower frequencies ranging from 125Hz to 2000Hz.

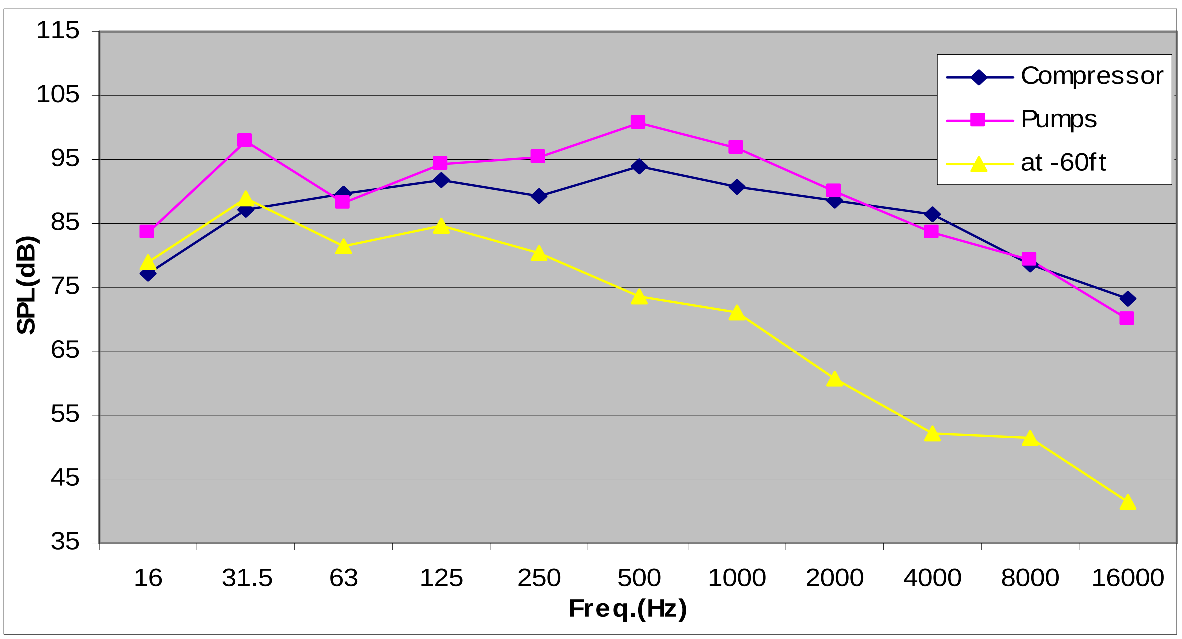


Figure 3.14 OBA at Power Pack Unit

Figure 3.14 also proved the declining of the overall noise at a distance 60 ft away from the power pack unit, which is a general phenomenon of sound. But the dominance of low frequency is still experienced. The shifting of high SPL to lower frequency at 50 ft away from the power pack indicated that the entry surface absorbs high frequency sounds more than the low frequency ones.

3.3 Summary

Various noise survey methods are applied and have been compared and from the characterization graphs and data, it is clear that attenuation of signal with distance is frequency dependent, with stronger attenuation of higher frequencies with increasing distance from the source. Frequency dependence due to destructive interference also forms an important part of the weakening of a noise signal.

In a mine environment where the surface is uneven and there are many sources of reflection therefore it is difficult to evaluate any particular relation between the attenuation rate and distance.

After the noise parameters and the characterization were determined, fundamental analysis was applied to the noise signals to show how the sound pressure level varied as a function of frequency. The analysis revealed that the frequency distribution of the prominent sound pressure levels occurred within the 0 to 2000 Hertz range. It was also found that the 125Hz to 600Hz are consistent dominant frequencies.

The noise results were further analyzed to determine the influence of various factors on the sound levels. Since the operations of the stage loader were not controlled in any particular manner, it was difficult to differentiate between the causes of the variability in the measured stage loader. Thus, no definite conclusions could be drawn as to the effect of production rate, coal seam or the time of day, on the measured sound levels. However, it can be confidently said that major contribution was from the lower frequency.

Both noise surveys were in the typical Pittsburgh seam geo-mining conditions used for the proposed research. The existence of low frequencies was found to be dominant well in both Mine A and Mine B regions. Thus with all these data and noise characterization study, a better understanding of reasonable solution and regulation needed is developed.

Therefore the approach with two applications is needed: (1) Controlling high frequency noise with passive control; (2) Canceling low frequency noise with engineering control (Active noise control). Since the Passive control fails to control the low frequency, it was decided to develop Active noise control technology in this research.

CHAPTER

4 ACTIVE NOISE CANCELLATION TECHNOLOGY

4.1 Introduction

Based on the characteristics of the noise sources in the longwall faces, efforts have been made to develop engineering controls to reduce the noise levels for the major noise sources and the working locations where the miners spend most of their times. There are two possible approaches to reduce the noise: passive and active. The conventional noise controls are based on the passive approach such as enclosures, barriers etc to attenuate unwanted noise. However, they could be costly, require large space and are ineffective at low frequencies, making some of the passive control methods often impractical. In this research, the emphasis is placed on studying the applicability and effectiveness of the active noise cancellation (ANC) technology for the crusher/stage loader assembly – one of the noisiest machines in a longwall face.

Real-time active noise cancellation is a relatively new field in the mining industry even though it has been successfully applied in some other industries. The schematic drawing of ANC technology is shown in Fig. 4.1. As the source noise travels through a duct, it is detected by the input microphone and the electronic signal is fed into the ANC controller. The characteristics (i.e., sound pressure level, frequency and phase) of the source noise are analyzed by the controller. The anti-noise (or control noise), similar to the source noise but in opposite phase, is generated by the ANC controller and speaker and released into the duct at proper location. The mixing of the source noise and anti-noise waves will result in a sound field with reduced sound pressure level (residual noise).

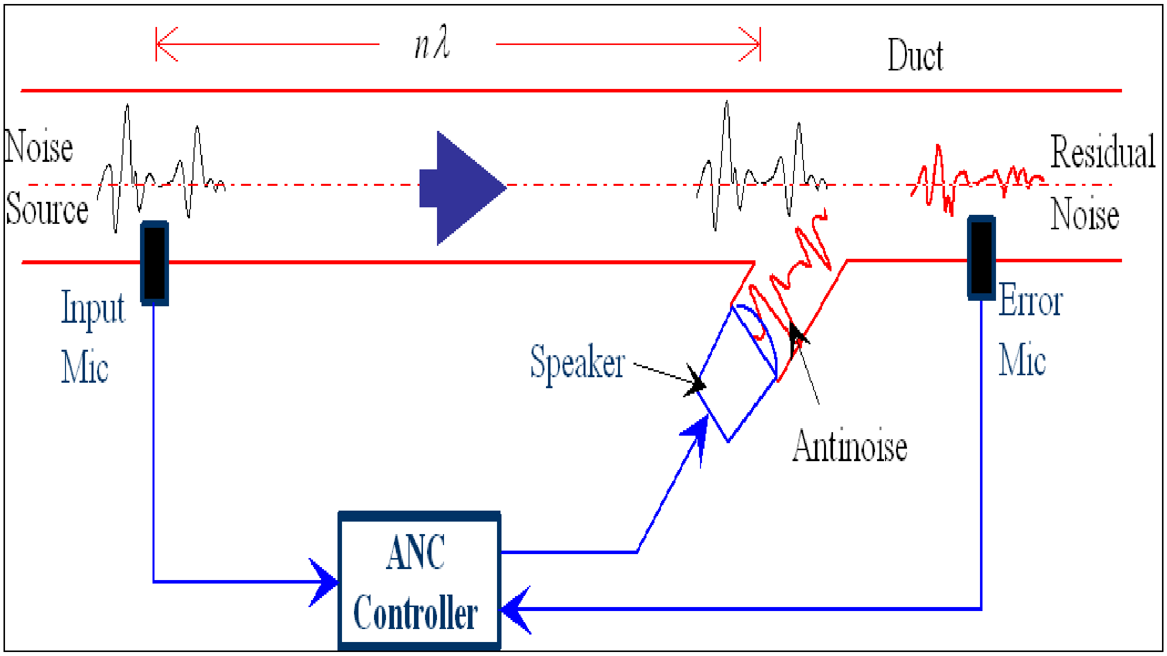


Fig 4. 1 *Schematic of feed forward active noise control system in a duct*

4.2 LABORATORY SET UP

As stated previously, the engineering noise controls can be classified into the passive controls and active noise controls. Due to the impracticalities of using passive noise controls in reducing the low frequency noises - dominant for some of the longwall machines, emphasis of this research is to study the applicability and effectiveness of active noise controls (ANC) to some of the longwall machines. Among the machines, the crusher and stage loader assembly is selected as the target of the study for the following reasons:

- It is often one of the noisiest machines in and around the longwall faces.
- More workers will spend more working time in and near this location.
- It is easy to create “ducts”, with some minor and inexpensive changes to the machines that can maintain the “standing” noise waves required to apply the ANC technology successfully and effectively.

The ANC methods are most promising to attack the noise field in an enclosed linear space, such as ducts, where noise standing waves can be maintained along its propagation path. A noise standing wave is that its characteristics The characteristics of a standing (i.e., sound pressure level, frequency and phase) will maintain nearly unchanged along its path. By maintaining standing wave in a duct, the noise filed becomes an essentially one-dimensional problem and can be attacked more readily using the ANC technology. In order to maintain such standing wave in the duct, the largest duct cross-sectional dimension of the duct should be one quarter of the wave length ($\lambda/4$) of the highest frequency of the noise to be reduced (Bies and Hansen, 2003).

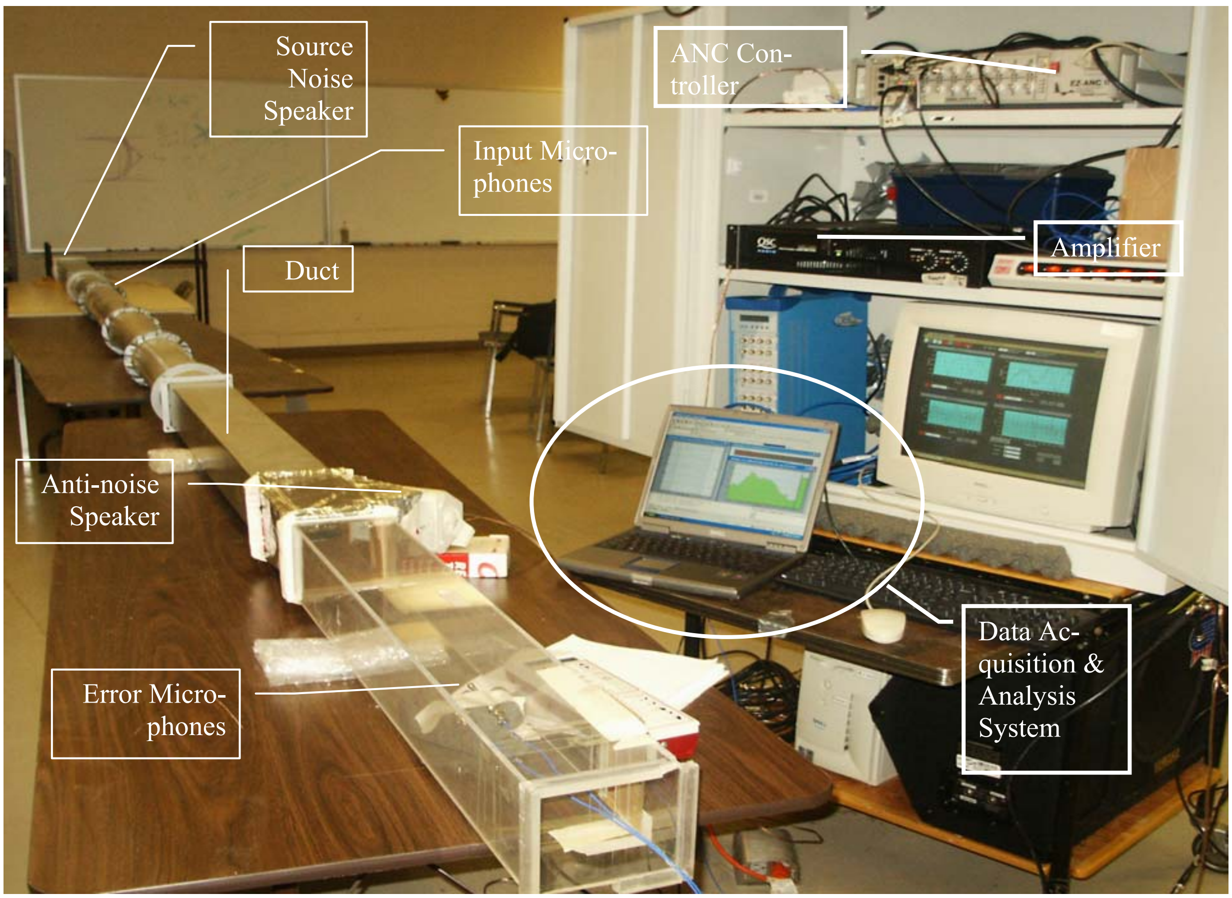


Fig 4.2 *The laboratory setup of the ANC experiment*

As stated before, ANC technology could be successfully applied on those machines where the noise propagates in a "duct" of proper cross-sectional size. Among the machines in a longwall face, the crusher/stage loader assembly is considered as the best candidate for the application of ANC technology. Noises generated by the motors, the coal crushing actions in the crusher, and the rubbing actions between the flight bars and the pans travels inside the steel enclosure and exits at the both end openings. This phenomenon is clearly demonstrated in Fig. 3.4 where the zones of high noise are located near both ends of the machine assembly. It must be noted that noise also radiates directly off of the crusher enclosure and the machine walls. However, this study is focused only on the internal noise source emitted from the ends of the machine – the main contributor to the noisy environment in the headgate T-junction area. The studies of applying ANC technology has been carried out in laboratory experiments in a steel duct that simulates the part of the open space on the carrying side of the stage loader.

Figure 4.2 shows the laboratory setup of the ANC experiment with a steel duct system used as the noise traveling path. In this duct system, both rectangular and circular ducts, with the same diagonal distance, are used. The previous research shows that the shape and surface do not affect the nature of the standing wave (Bies and Hansen, 2003). The rectangular portions of the duct were 11.4 cm wide, 12.7 cm high while the circular portion has a diameter of 17 cm. Based on the λ/4 rule, the shortest wavelength in the standing wave would be (4 x 17 cm = 68 cm). Therefore, the highest frequency of the noise that can be effectively cancelled in the duct will be 506 Hz since the speed of sound in air is 344 m/s. The length of the duct system was 6.3 m.

Fig 4.3 *Tailpiece end of a stage loader*

To match the need of creating a standing wave within a duct, longwall stage loader proved to be the most promising candidate for ANC application (fig 4.3).

Figure 4.4 is a snapshot of the equipments used in the ANC laboratory experiments. They are (L to R) EZ-ANC II and OROS (OR38) Analyzer. The experiments were performed on fourteen noise segments that were recorded inside an operating longwall stage loader with each of them being about 30 seconds long. The source noise was produced by a computer-driven speaker placed at one end of the duct. The input microphone was placed about 1.2 m away from the source speaker and connected to an EZ-ANC II controller. The ANC controller analyzes the source noise as well as the residual noise from the feedback error microphone. It then sends signals to the anti-noise speaker to generate the canceling noise into the duct system. The error microphone located near the exit of the duct also monitors the noise leaving the duct system for assessing the effectiveness of the noise reduction efforts.

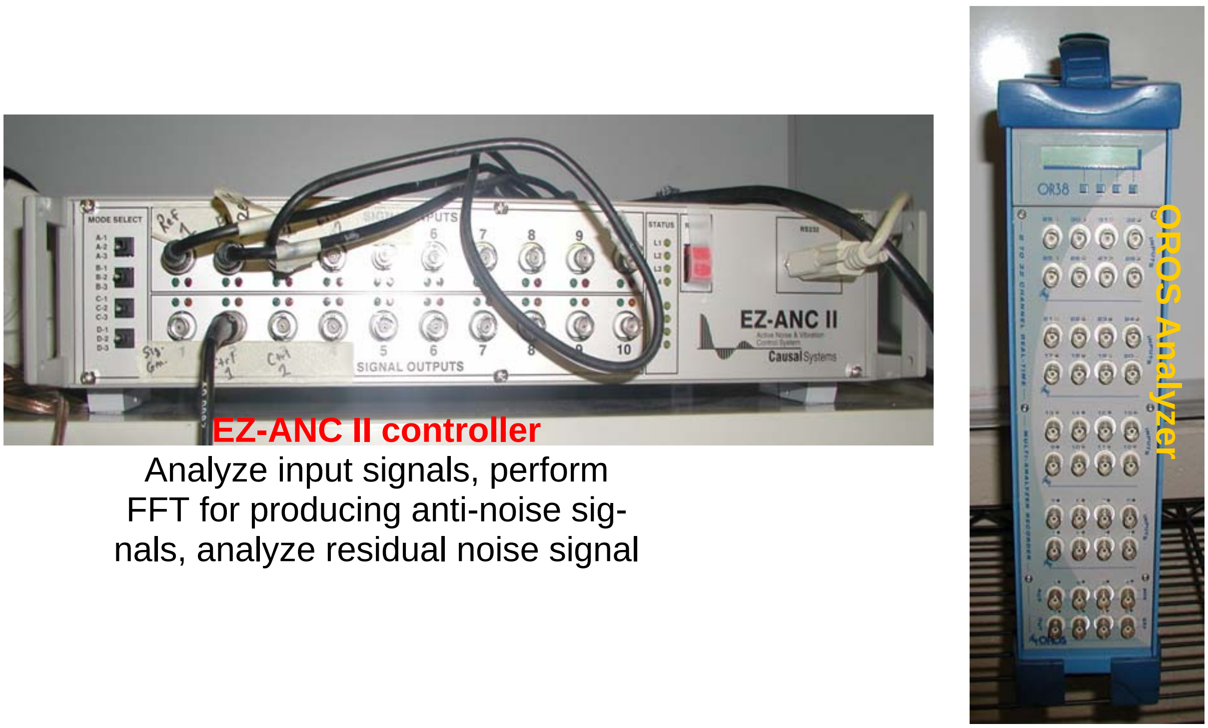


Fig 4.4 *Equipments used in ANC laboratory experiments*

The EZ-ANC II controller is a semi-automatic system requiring manual inputs for many of the control parameters. The main objective of the laboratory studies is to find the set of control parameters that produce the best reduction effect for a given noise field. There are so many parameters to be controlled manually but only some important ones are cited in this paper. Extensive experiments were carried on one of the recorded noise segments to find a desirable set of parameters. Then this set of control parameters were applied to the other recorded noise segments. Table 4.1 shows nine sets of tests performed on two noise segments (seven on segment A and two on segment B) with two important control parameters listed.

The cancellation path transfer function checks the relation between control signal leaving the digital control filter and re-entering the control as an error signal. The base convergence coefficient (BCC) is one of the most important parameter in this function. It is basically a measure of how hard the adaptive control system should be forced to perform. The update rate in the cancellation path id is used to control the actual modeling rate. Another important control parameter, the base leakage value (BLV), is found to be the best at a fixed value of 0.001 for the experiments performed.

Figure 4.5 shows a snapshot of manual input screen for EZ-ANC II controller. The variety of parameters can be adjusted as per need of the experiment. It is very important to get a balance and match the values with proper weightage needed by the control panel.

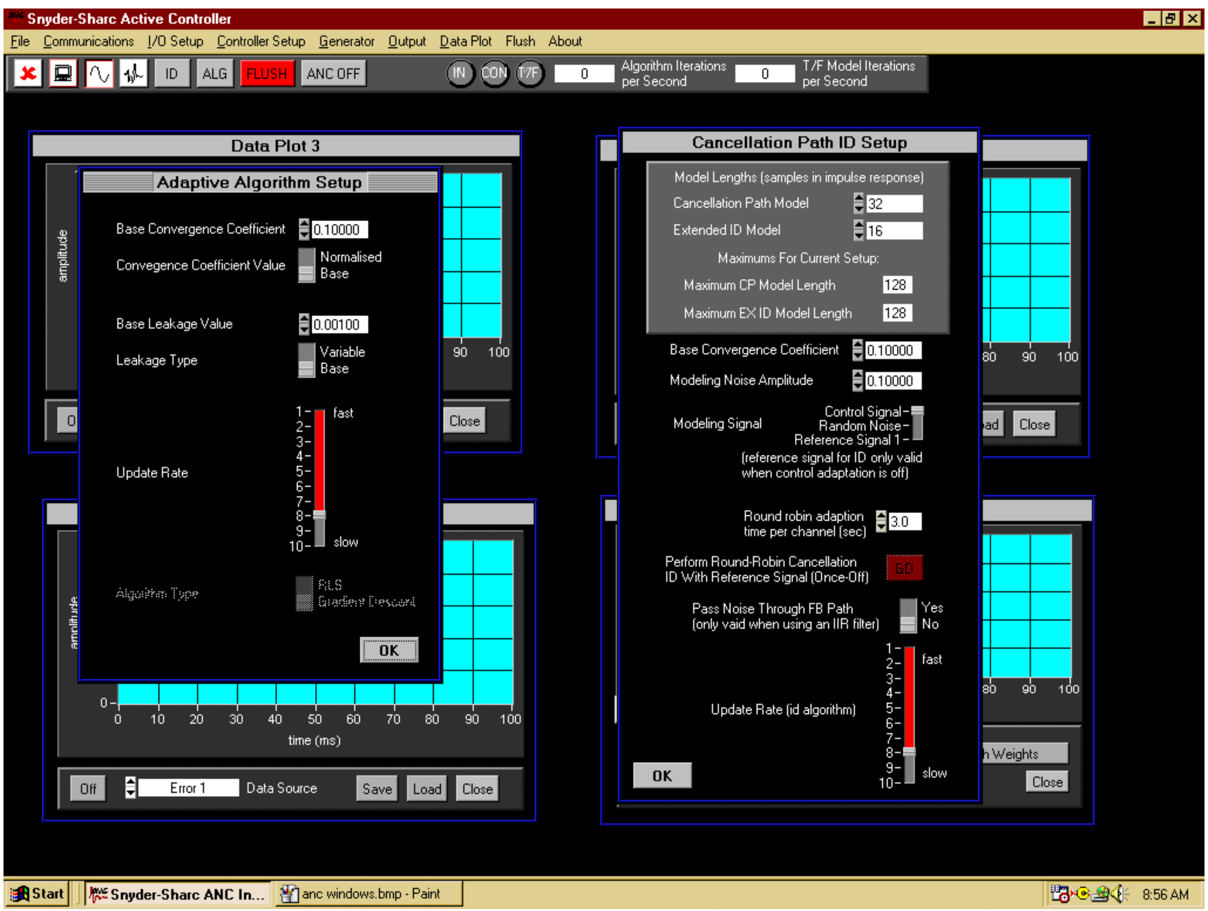


Fig 4.5 *Manual input screen for EZ-ANZ II controller*

For the nine sets of tests presented in this paper the base convergence coefficient ranges from 0.10 to 0.35 while the update rate ranges from 5 to 8. For the two tests performed on noise segment B (T15A and T16), the same parameters were used but the weights are (were) manually adjusted so that the sound volume of the anti-noise speaker can match with the source noise. Figure 4.6 presents the results screed capture of the OROS octave band analyzer.

Table 4.1 *Testing parameters and noise reductions*

Test No.	Noise Segment	BCC	Update Rate	Overall Reduction dB	Reduction at Sampling Point	
					dB	dBA
10	A	0.01	5		5.5	-0.9
11	A	0.35	6		5.5	1.0
12	A	0.25	6		5.5	0.5
13	A	0.25	8		6.0	1.0
14	A	0.20	8		7.0	1.7
15	A	0.15	8	9.6	9.3	3.1
15A	B	0.15	8	7.3	7.3	2.8
16	B	0.15	8	9.3	7.9	2.7
17	A	0.10	6	7.7	7.9	1.9

Figure 4.7 shows the average sound levels measured with a sound level meter near the exit end of the duct system for noise segment A with and without the ANC controller turned on. Without the ANC turned on (the original noise), the noise level varied from 97.2 dB to 100.3 dB. For this segment, the sound level was higher in the first 12 seconds than that in the remaining duration. In the tests with the ANC turned on, the average sound level

for test T15 ranged from 87.0 to 91.1 dB with an overall noise reduction of 9.6 dB as shown in Table 4.1. For test T17, the residual sound level was reduced to between 89.6 and 92.7 dB with the overall reduction being 7.7 dB.

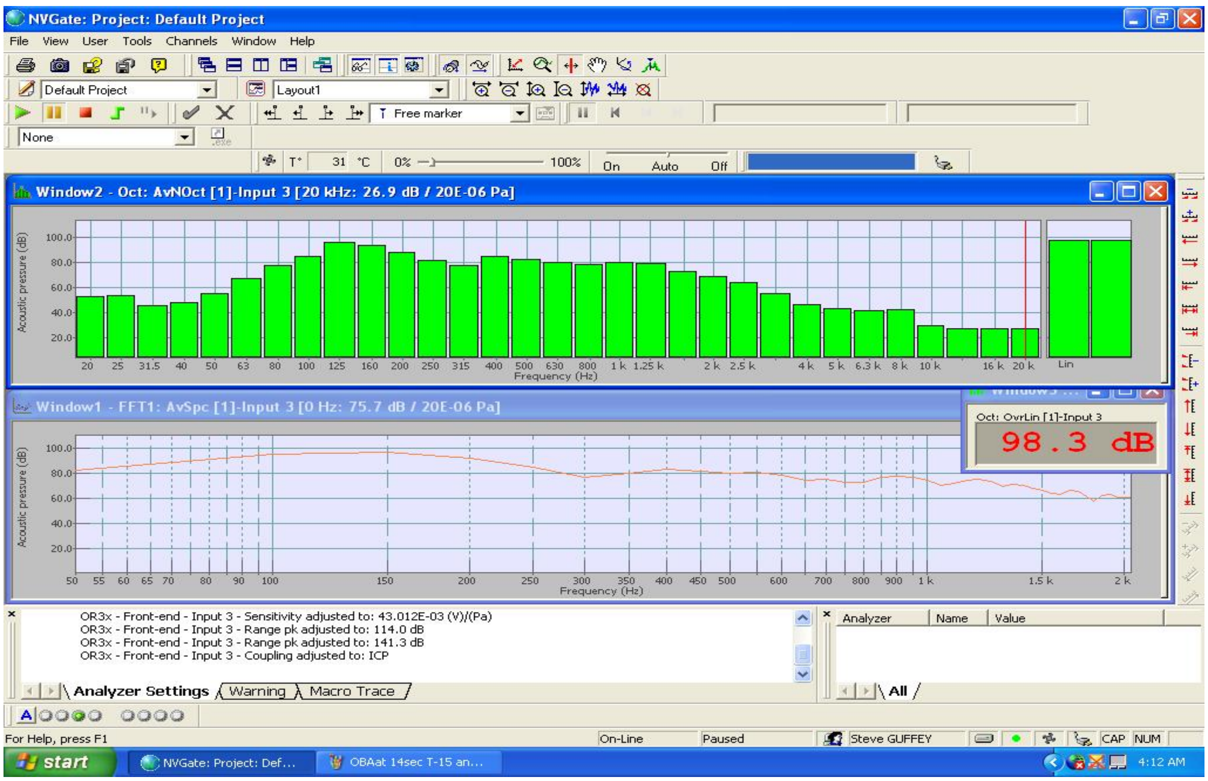


Fig. 4.6 *Result screen capture of the OROS octave band analyzer.*

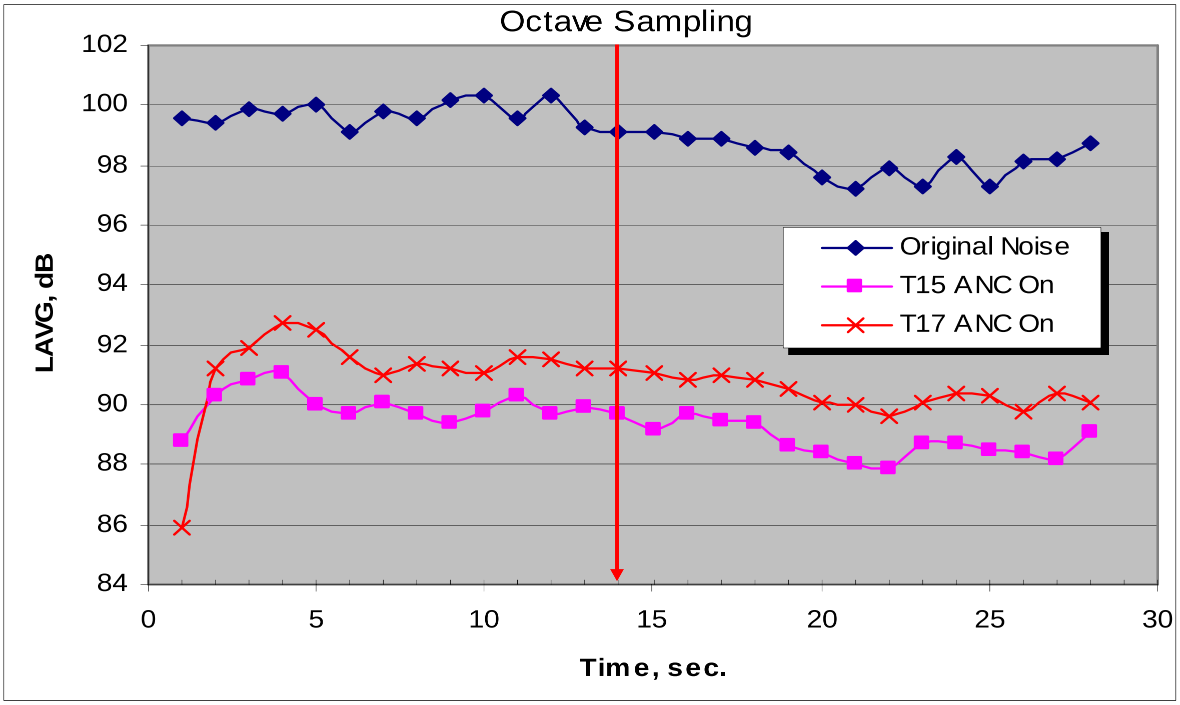


Fig. 4.7 *Measured on segment A of the recorded stage loader noise*

The ANC controller has (had) also been set to attack the high noise level in the frequency range from 100 Hz to 650 Hz. In order to show the effects, samples were taken, using the data acquisition system, from the noise segment A at the time point t = 14 s for each of the tests. Octave band analyses were performed on the sampled data and the results are plotted in Fig. 4.8. For noise segment A, the peak sound pressure level before the ANC controller was turn on was in the frequency range from 100 to 250 Hz. The tests with ANC turned 'on' show that all except test T10 (shows that except test T10 all others tests) were successful, at varying degrees, in reducing the noise level in the peak noise range. In test T10, due to its small base convergence coefficient (BCC = 0.01) and slow update rate (5), the noise reduction in the peak range was not significant. The reduced sound pressure levels for the tests are plotted in Fig. 4.9. It shows significant reductions were achieved in the frequency range from 80 to 250 Hz for all the tests except for test T10. For tests T14 and T15, the upper limit of the frequency range where significant reductions were observed was even extended to 630 Hz. The largest noise reduction, 21.4 dB, was achieved in test T15 at the frequency of 125 Hz. In this test, the BCC and update rate were set at 0.15 and 8, respectively. Figure 4.9 also show that for significant negative reductions, up to -5.7 dB, were observed in the frequency range from 1,250 to 3,150 Hz for tests T11 and T12 in which the BCC were set at higher values (0.35 and 0.25, respectively). The linearly average and the A-weighted noise reductions at the sampling point for all the tests are also listed in Table 4.1. The linearly average reductions on noise segment A range from 5.5 to 9.3 dB with test T15 being the best. The A-weighted reduction for test T15 is a significant 3.1 dBA. Based on the tests performed, the control parameters of BCC = 0.15, BLV = 0.001 and the update rate at 8 appeared to achieve the best noise reduction on noise segment A.

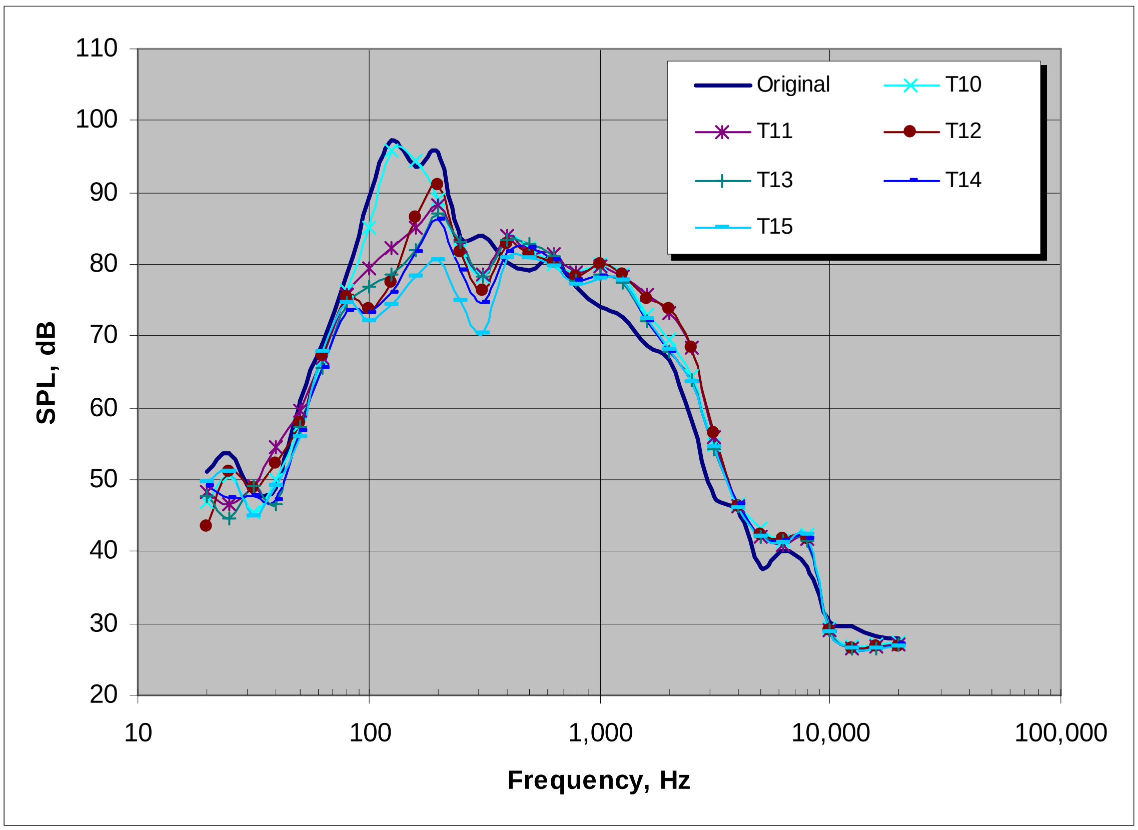


Fig 4.8 *Measured sound pressure levels vs. frequency for various tests on noise segment A*

Tests were also performed to resolve the undesirable negative reduction problem in the higher frequency range (1,250 to 3,150 Hz) in tests T11 and T12 (Fig. 4.10) by targeting the ANC algorithm in that frequency. These tests were performed with the same basic control parameters as before but with selected higher frequency range. The tests achieved reductions between zero and 0.8 dB in the high frequency range from 1 kHz to 20 kHz. Although the reductions are not significant, they eliminated the negative reduction problems in the previous two tests. On the other hand, these tests show that to use ANC technology to reduce high frequency noise is indeed ineffective.

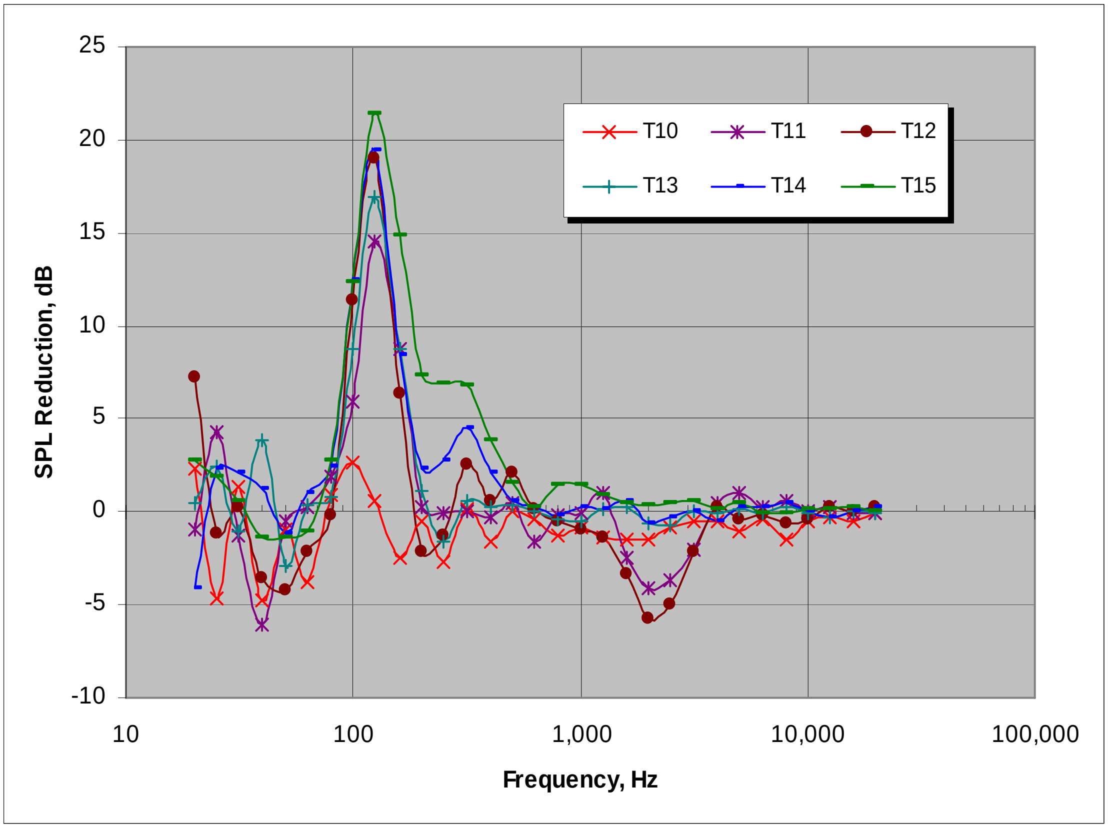


Fig.4.10 *Reductions on sound pressure levels at different frequency sampled at t = 14 seconds on noise segment A*

In order to check the applicability of the best set of control parameters previously determined (the ones used in test T15) to the other noise segments, they were used in two tests (T15A and T16) performed on noise segment B. Between these two tests, the weights that control the anti-noise speaker volume are also varied. The measured average SPL before and after application ANC algorithms is plotted against the time in Fig. 4.11. The overall reductions for the 28-second long noise segment are 7.3 and 9.3 for tests T15A and T16, respectively.

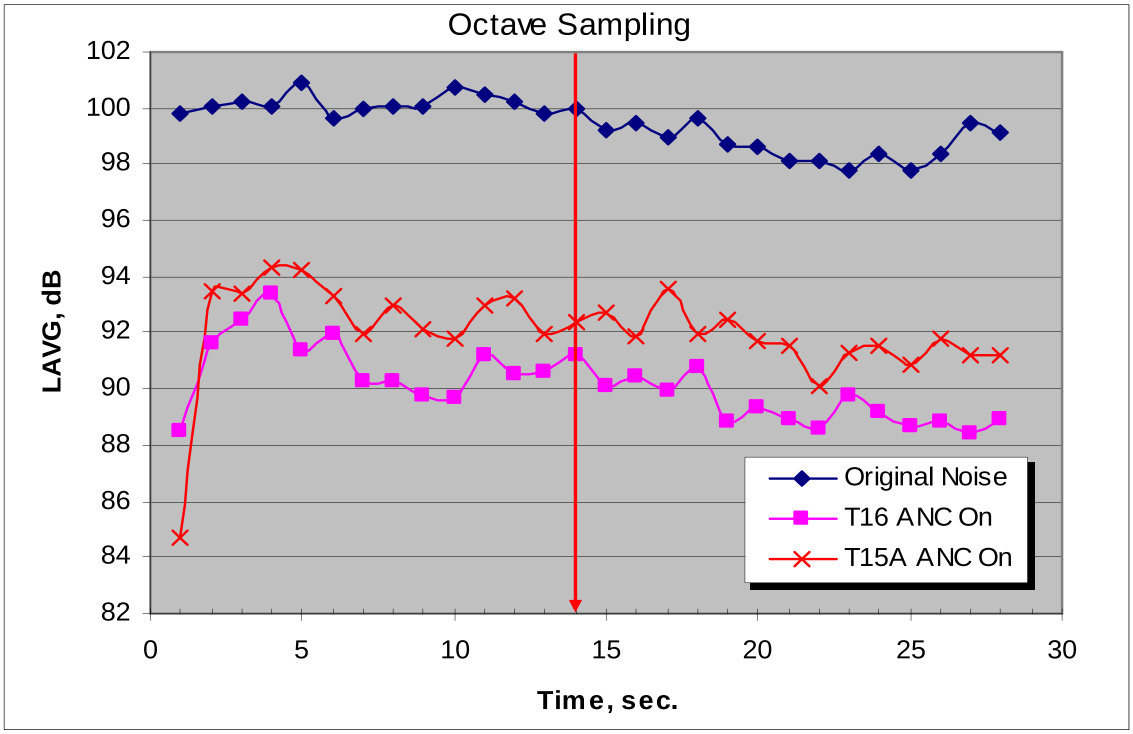


Fig 4.11 *Reductions on segment B of the recorded stage loader noise*

Octave band samplings were also performed at the time point t = 14 s in test T16. The SPL-frequency distributions at the sampling point before and after ANC is applied as well as the noise reductions are shown in Fig. 4.12 Again, the most significant noise reduction was achieved in the frequency range from 90 to 630 Hz with the maximum reduction of 25 dB at the frequency of 125 Hz. The linearly and A-weighted average noise reductions for test T16 are 7.9 dB and 2.7 dBA, respectively.

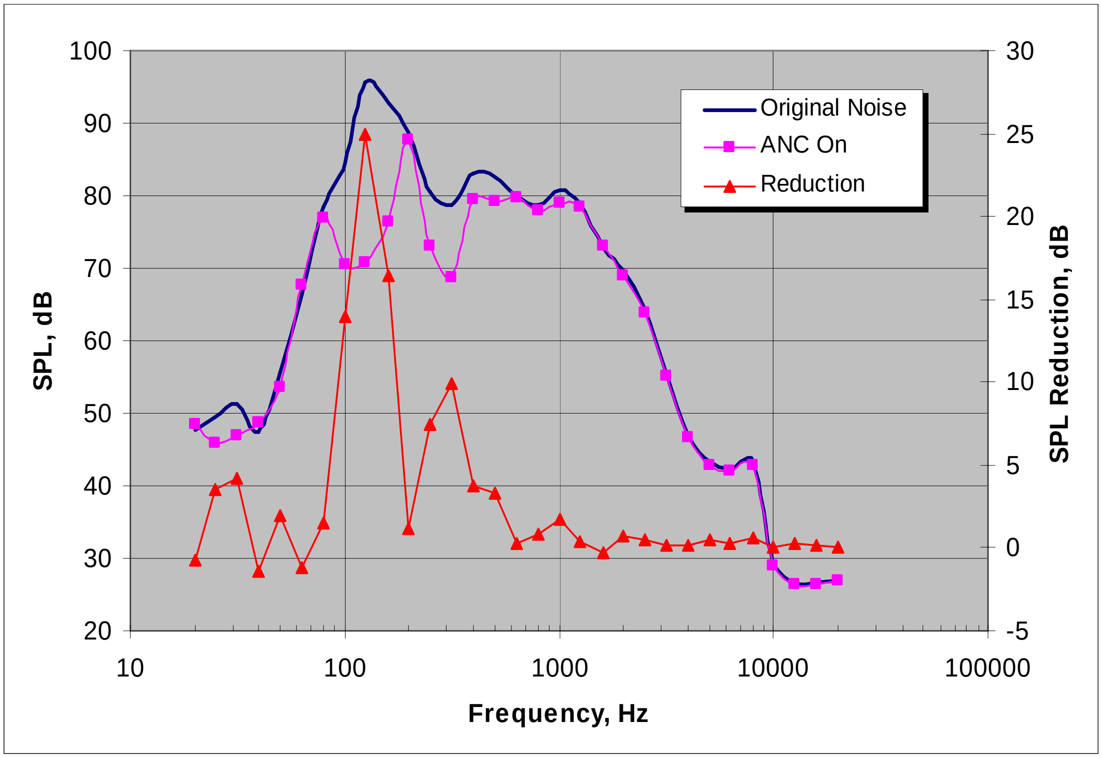


Fig 4.12 *Measured sound pressure levels and reduction for test T16 on noise segment B*

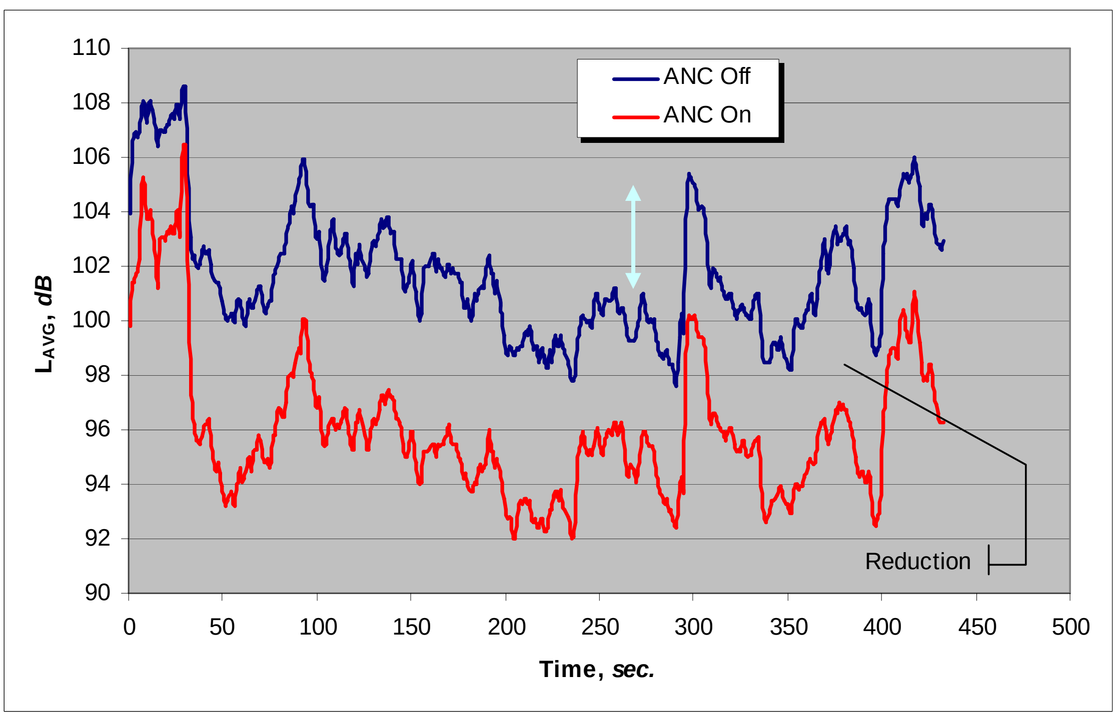


Fig 4.13 *Tests performed on all 14 noise segments with the control parameters used in test T15*

One additional test has also been conducted when all the 14 recorded noise segments are joined together. The control parameters that have been used in test T15 are implemented in this test. The results before and after the ANC algorithm is applied are shown in Fig. 4.13. It shows that ANC is capable of reducing the noise level for every noise segment and the overall reduction in the 433-second duration is 5.7 dB.

4.3 Chapter Summary

For the Laboratory set-up and the other parameters considered in this work, the following are the significant observations with regard to the influence of the low frequencies on overall SPL and effectiveness of ANC technology with stability and reliability:

- In general, the most of the machinery used in longwall face showed a similar frequency spectrum i.e. high dominant low frequencies. However, depending on the available processors and the present technology maximum use of ANC technology is very limited.
- ANC can work much better for the lower frequencies upto 800HZ. Again, depending on the set-up conditions discussed in the previous sections, minimum and maximum cancellation results may be seen upto 1000Hz.
- The cancellation effects depend on the various parameter set-ups like maximum overall SPL, maximum dominant frequencies, location of the microphones in the layout and the location of the noise source, etc.
- For the ANC laboratory set-up considered in this research, it was seen that the reflection noise can be minimized with use of porous tubes at the reference microphone.
- In general, ANC results noticed in the previous research corroborated the findings in this chapter.
- Also, these results found for the random noise direct a new direction of a possible engineering control through ANC technology in the mining industry.

CHAPTER

5 CONCLUSIONS AND FUTURE RESEARCH

The reliability of an engineering noise control depends on many factors and methods available, the ANC technology is one among them. Till recent, there are some good works available in the published literature as discussed in chapter 2, also other industries have successfully applied ANC technology. This thesis is an endeavor made to explore the solid chance of adapting ANC technology in the mining industry. The results of this research have been summarized below . Considering the limited nature of this thesis, still many parameters are yet to be explored. A suggestion for the possible areas for future research is also envisaged and recommendations for possible design consideration are included.

5.1 Thesis Conclusions

The following conclusions can be drawn from this noise research:

Field noise surveys have been conducted to characterize the noise field in and around the longwall faces. It is found that the crusher/stage loader assemblies are usually the noisiest machines in a most congested area in the longwall face. The octave band analysis showed lower frequencies (100 Hz -650 Hz) as dominant frequencies.

The crusher/stage loader is selected for ANC application. Extensive and systematic laboratory experiments have been conducted on the noise segments recorded from longwall stage loaders. The experiments have shown that the ANC can achieve significant noise reductions if proper control parameters have been used. The frequency range within which the noise reductions are significant is from 100 Hz to 650 Hz – consistent with the dominant frequency range of most longwall noise sources. The overall noise reductions are in the range from 5.5 dB to 9.3 dB.

However, the ANC was not very effective in reducing the portion of the noise in frequency larger than 1,000 Hz at the current stage of our research. A combined approach using both the active and passive noise (more effective for high frequency noise) controls would be preferred. For example, by adding mass and vibration dampening to the crusher/stage loader can reduce the noise level where the controls are added. Then the ANC could be used to reduce the noise that is channeled down the stage loader.

Recommendations for Design considerations:

- Use of longer stage loaders: A proper size of stage loader should be selected, if the geo-mining conditions permit. Longer the better, as the source of noise is at a larger distance and exposure to the operator is reduced to a considerable level.
- Headgate Operator can be provided with a good seat at the control panel and if possible an enclosure cabin can be designed. This can psychologically help the operator to rest and spend more time on the seat when he is free.
- Good database of machine noise surveys should be maintained and a optimum relation can be drawn for maintenance requirement based on the noise source of the different parts. Also, replacement of machines can be designed after certain number of maintenance cycle.

5.2 <u>Future Research</u>

For the lucid understanding of ANC technology and its effectiveness in the mining industry, the following factors still need to be considered in order to develop a more reliable noise control technology:

- Availability of more advanced processors and microphones.
- Understanding low frequency spectrum for all machines used in the underground mining industry.
- The effect of confinement, temperature and dust, etc.

- The effect of ducts dimension on the ANC response must also be incorporated.
- In mining industry, very limited noise recording instruments are available due to intrinsic safety legality. There is a need for more advanced digital real time noise recording instrument.

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GLOSSARY

Where possible, the definition is quoted from the appropriate American National Standards Institute (ANSI) standard, ANSI S1.1-1994 [ANSI 1994] or ANSI S3.20-1995 [ANSI 1995], under the term(s) used in that standard.

Audiogram: Graph of hearing threshold level as a function of frequency (ANSI S3.20-1995: audiogram).

Baseline audiogram: The audiogram obtained from an audiometric examination administered before employment or within the first 30 days of employment that is preceded by a period of at least 12 hr of quiet. The baseline audiogram is the audiogram against which subsequent audiograms will be compared for the calculation of significant threshold shift.

Continuous noise: Noise with negligibly small fluctuations of level within the period of observation (ANSI S3.20-1995: stationary noise; steady noise).

Crest factor: Ten times the logarithm to the base ten of the square of the wideband peak amplitude of a signal to the time-mean-square amplitude over a stated time period. Unit, dB (ANSI S3.20-1995: crest factor).

Decibel (dB): Unit of level when the base of the logarithm is the 10th root of 10 and the quantities concerned are proportional to power (ANSI S1.1-1994: decibel).

Decibel, A-weighted (dBA): Unit representing the sound level measured with the A-weighting network on a sound level meter. (Refer to Table 4-1 for the characteristics of the weighting networks.)

Decibel, C-weighted (dBC): Unit representing the sound level measured with the C-weighting network on a sound level meter. (Refer to Table 4-1 for the characteristics of the weighting networks.)

Derate: To use a fraction of a hearing protectors noise reduction rating (NRR) to calculate the noise exposure of a worker wearing that hearing protector. (See NRR below.)

Dose: The amount of actual exposure relative to the amount of allowable exposure, and for which 100% and above represents exposures that are hazardous. The noise dose is calculated according to the following formula:

$$D = [C_1/T_1 + C_2/T_2 + ... + C_n/T_n] \text{ H } 100$$

Where

- C_n = total time of exposure at a specified noise level T_n = exposure time at which noise for this level becomes hazardous

Effective noise level: The estimated A-weighted noise level at the ear when wearing hearing protectors. Effective noise level is computed by (1) subtracting derated NRRs from C-weighted noise exposure levels, or (2) subtracting derated NRRs minus 7 dB from A-weighted noise exposure levels. Unit, dB. (See Appendix.)

Equal-energy hypothesis: A hypothesis stating that equal amounts of sound energy will produce equal amounts of hearing impairment, regardless of how the sound energy is distributed in time.

Equivalent continuous sound level: Ten times the logarithm to the base ten of the ratio of time-mean-square instantaneous A-weighted sound pressure, during a stated time interval *T*, to the square of the standard reference sound pressure. Unit, dB; respective abbreviations, TAV and TEQ; respective letter symbols, L_{AT} and $L_{\mathrm{Aeq}T}$ (ANSI S1.1-1994: time-average sound level; time-interval equivalent continuous sound level; time-interval equivalent continuous A-weighted sound pressure level; equivalent continuous sound level).

Excess risk: Percentage with material impairment of hearing in an occupational-noise-exposed population after subtracting the percentage who would normally incur such impairment from other causes in a population not exposed to occupational noise.

Exchange rate: An increment of decibels that requires the halving of exposure time, or a decrement of decibels that requires the doubling of exposure time. For example, a 3-dB exchange rate requires that noise exposure time be halved for each 3-dB increase in noise level; likewise, a 5-dB exchange rate requires that exposure time be halved for each 5-dB increase.

Fence: The hearing threshold level above which a material impairment of hearing is considered to have occurred.

Frequency: For a function periodic in time, the reciprocal of the period. Unit, hertz (Hz) (ANSI S1.1-1994: frequency).

Hearing threshold level (HTL): For a specified signal, amount in decibels by which the hearing threshold for a listener, for one or both ears, exceeds a specified reference equivalent threshold level. Unit, dB (ANSI S1.1-1994: hearing level; hearing threshold level).

Immission level: A descriptor for noise exposure, in decibels, representing the total sound energy incident on the ear over a specified period of time (e.g., months, years).

Impact: Single collision of one mass in motion with a second mass that may be in motion or at rest (ANSI S1.1-1994: impact).

Impulse: Product of a force and the time during which the force is applied; more specifically, impulse is the time integral of force from an initial time to a final time, the force being time-dependent and equal to zero before the initial time and after the final time (ANSI S1.1-1994: impulse).

Impulsive noise: Impulsive noise is characterized by a sharp rise and rapid decay in sound levels and is less than 1 sec in duration. For the purposes of this document, it refers to impact or impulse noise.

Intermittent noise: Noise levels that are interrupted by intervals of relatively low sound levels.

Noise: (1) Undesired sound. By extension, noise is any unwarranted disturbance within a useful frequency band, such as undesired electric waves in a transmission channel or device. (2) Erratic, intermittent, or statistically random oscillation (ANSI S1.1-1994: noise).

Noise reduction rating (NRR): The NRR, which indicates a hearing protectors noise reduction capabilities, is a single-number rating that is required by law to be shown on the label of each hearing protector sold in the United States. Unit, dB.

Permanent threshold shift (PTS): Permanent increase in the threshold of audibility for an ear. Unit, dB (ANSI S3.20-1995: permanent threshold shift; permanent hearing loss; PTS).

Pulse range: Difference in decibels between the peak level of an impulsive signal and the root-mean-square level of a continuous noise.

Significant threshold shift: A shift in hearing threshold, outside the range of audiometric testing variability (5 dB), that warrants followup action to prevent further hearing loss. NIOSH defines significant threshold shift as an increase in the HTL of 15 dB or more at any frequency (500, 1000, 2000, 3000, 4000, or 6000 Hz) in either ear that is confirmed for the same ear and frequency by a second test within 30 days of the first test.

Sound: (1) Oscillation in pressure, stress, particle displacement, particle velocity, etc. in a medium with internal forces (e.g., elastic or viscous), or the superposition of such propagated oscillations. (2) Auditory sensation evoked by the oscillation described above (ANSI S1.1-1994: sound).

Sound intensity: Average rate of sound energy transmitted in a specified direction at a point through a unit area normal to this direction at the point considered. Unit, watt per square meter (W/m^2); symbol, I (ANSI S1.1-1994: sound intensity; sound-energy flux density; sound-power density).

Sound intensity level: Ten times the logarithm to the base ten of the ratio of the intensity of a given sound in a stated direction to the reference sound intensity of 1 picoWatt per square meter (pW/m^2). Unit, dB; symbol, *L* (ANSI S1.1-1994: sound intensity level).

Sound pressure: Root-mean-square instantaneous sound pressure at a point during a given time interval. Unit, Pascal (Pa) (ANSI S1.1-1994: sound pressure; effective sound pressure).

Sound pressure level: (1) Ten times the logarithm to the base ten of the ratio of the time-mean-square pressure of a sound, in a stated frequency band, to the square of the reference sound pressure in gases of 20 micropascals (µPa). Unit, dB; symbol, L_p. (2) For sound in media other than gases, unless otherwise specified, reference sound pressure in 1 µPa (ANSI S1.1-1994: sound pressure level).

Temporary threshold shift: Temporary increase in the threshold of audibility for an ear caused by exposure to high-intensity acoustic stimuli. Such a shift may be caused by other means such as use of aspirin or other drugs. Unit, dB. (ANSI S3.20-1995: temporary threshold shift; temporary hearing loss).

Time-weighted average (TWA): The averaging of different exposure levels during an exposure period. For noise, given an 85-dBA exposure limit and a 3-dB exchange rate, the TWA is calculated according to the following formula:

$$\text{TWA} = 10.0 \text{ H Log}(D/100) + 85$$

where D = dose.

Varying noise: Noise, with or without audible tones, for which the level varies substantially during the period of observation (ANSI S3.20-1995: nonstationary noise; nonsteady noise; time-varying noise).