Active noise control of stageloader noise in Longwall Mining

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Abstract

With the large-scale mechanization inherent to the mining industry, noise-induced hearing loss remains a major concern. As part of ongoing efforts to develop engineering controls to reduce noise levels in longwall mining, active noise-control experiments were conducted above ground on a modified nonworking stageloader. Recorded underground stageloader noise was broadcast to the aboveground stageloader. When active noise control was applied, the result was an average 7 dBA reduction. These results suggest that active noise reduction could be a useful means to reduce stageloader noise if the control system can be made sufficiently rugged.

Introduction

Exposure to noise doses above established thresholds can cause irreparable sensori-neural damage to the auditory system. Substantial hearing loss can have strong adverse effects, including the insidious personal and social consequences associated with difficulties in communicating with others (Royster and Royster, 2000). Although properly worn hearing protectors can sharply reduce the effects of unprotected noise exposure, it is commonplace to observe hearing loss in miners who have worked even a few years, perhaps because they have not always worn their plugs or muffs properly when exposed or because their hearing protection was less than effective under the conditions of mining.

A National Institute for Occupational Safety and Health (NIOSH) study published in 1996 reported that hearing loss in miners was significantly worse than in the non-occupationally noise-exposed population despite decades of engineering interventions and use of hearing protection. By age 30, the range of loss of hearing in miners was equivalent to that of those who are 51 years old but have not been exposed to high levels of noise on the job. By 50 years of age, 90% of miners have substantial hearing impairment. By contrast, only 50% of 69-year-old non-exposed people have a similar hearing impairment (NIOSH, 1996).

Given the continued loss of hearing in miners despite the widespread use of hearing protection, it is important to reduce noise levels to below 85 dBA. Because hearing loss increases sharply with the level of noise, it is also important to reduce noise levels as much as feasible, even in cases where noise levels cannot be reduced to 85 dBA or less. For that reason, the Mine Safety and Health Administration (MSHA) historically has pressed for engineering changes that could produce even modest noise reductions (e.g., 3 dBA), even when they have been difficult or costly.

Reducing noise is difficult in most industries, but the tight spaces and high mechanization of longwall coal mining makes noise reductions particularly challenging. MSHA has published numerous noise-control guides and reports to assist mine operators in noise control efforts (Bartholomae and Burks, 1996, MSHA, 1999), but much more progress is needed. Typical longwall coal mining crews are routinely exposed to more than 100% of the MSHA allowed noise dose.

One important source of noise in longwall mining is the stageloader, which is the primary source of exposure for the headgate operator and a secondary noise source for the rest of the crew who must pass by the stageloader repeatedly. Reducing exposure due to stageloaders is the objective of this noise-control investigation. For the study, noise characteristics from two stageloaders were investigated. Noise recorded from a stageloader was then used in tests of active noise controls of a modified, nonworking stageloader above ground.

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Background

As documented by MSHA inspectors in the noise dosimetry database (MSHA, 2004a), the arithmetic average noise dose for headgate operators working at a stageloader machine is 120.4%, with a range of 18% to 373%. The geometric mean is 100.2% and the geometric standard deviation of 1.87. It is important to understand that some operators are much more heavily exposed than others because the actual noise exposure level for a given operator depends on many variables, including the length of the stageloader and where the operator spends most of his or her time, as will be discussed below.

There have been attempts to reduce the noise exposures to stageloader operators. Noise reduction can be accomplished, in general, by the following: blocking the path of the noise, reducing the sound power generated by the source or producing a noise equal to the source noise but 180 degrees out of phase. The latter is called "active noise cancellation" and the rest are variants of "passive controls." The noise path can be blocked by ear protection, such as earmuffs or plugs or by barriers or enclosures between the source and the operator.

Passive noise controls. Ear muffs are almost universally worn by operators but are considered an inadequate solution for the reasons discussed above. Barriers, such as walls separating the stageloader from the operator, could be extremely effective if the walls completely separated the machine from the operator. However, given the need for at least occasional access to the stageloader, the undesirability of impeding air movement and the frequent need to move the stageloader, complete walls are problematic at best. Partial shields could be of some value when the operator is very close to the ends, a possibility that is part of the ongoing research by the authors.

Enclosing the entry and tail end of the stageloader while reducing noise emanating through the sides is a potentially highly effective means of reducing noise. To be effective, openings in the enclosure must be minimized and cannot face towards the operator. This would interfere with the operator's views of the machine. It may be possible to restore visual access using remote cameras inside the enclosures. However, the camera lens would be quickly coated with dust, reducing the usefulness of the cameras, perhaps to the point that the operator would open the enclosure to improve visual access.

Reducing the sound power always has the potential to dramatically reduce noise exposures but often involves severe tradeoffs. For example, the sound power from impacts of the coal on the stageloader could be reduced by cutting holes in the sides. However, this would allow noise now transmitted down the interior of the stageloader to issue from the sides, possibly increasing exposures.

Likewise, noise due to the chains could be reduced by coating them with an absorbent urethane. One unpublished study at NIOSH's Pittsburgh Research Laboratory investigated coating the flights on the chain conveyor of a continuous miner with a urethane material. The urethane provided significant noise reductions, and the material proved durable (Metatic and Reeves, 2003; Kovalchik, 2005). The coated flight bars are listed as a "promising" noise control by MSHA (MSHA, 2004b). MSHA defines "promising" as "having the potential for reducing sound levels or exposure time based on laboratory or limited field studies" (MSHA, 2004b). A case study is needed to move the coated flight bars to the technologically achievable list.

In another NIOSH unpublished study (Metatic and Reeves, 2003), researchers applied damping material to the exterior of a stageloader. Noise levels in the immediate area of the application were reduced, but noise at other locations along the stageloader increased. Continuing the application along the stageloader could conceivably send the noise out the tail end towards the belt entry. The stageloader is essentially a duct through which the coal is loaded out onto the belt. There is usually an air gap above the coal surface, at least up through the gooseneck. This air gap in a duct would be the medium through which the interior noise could be channeled when exterior passive noise controls are applied.

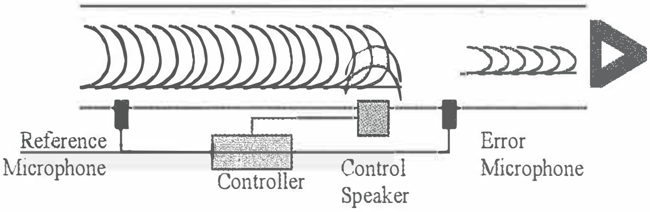

Figure 1 — Schematic of feed-forward active noise control system in a duct.

This discussion is not intended as a dismissal of the potential benefits of reengineering for noise reduction or of enclosures or partial barriers. It is conceivable that a feasible solution will some day emerge from these approaches. However, the progress to date has been modest and hard won. Furthermore, most passive methods are typically most effective with high-frequency noise (e.g., greater than 500 Hz) and least effective with lower-frequency noise. As discussed below, noise recorded from two operating stageloaders by the authors was dominated by low-frequency noise.

Active noise controls. The remaining method, active noise cancellation, has many practical difficulties and limitations of its own, but it does have potential for effectiveness in reducing low-frequency noise, which sometimes is difficult to control. For that reason, the authors explored the potential effectiveness of active noise cancellation to reduce noise emanating from a stageloader.

Active noise control (ANC) is a technique to reduce noise by creating a 180° out-of-phase noise signal to cancel the noise source. A diagram of a "feed-forward" ANC system in a duct is in Fig. 1. A reference microphone is used to sense the signal of noise traveling along the duct. The signal is analyzed at the controller using a fast Fourier transformation, and an out-of-phase sound is broadcast into the duct via a control speaker. An error microphone then picks up the residual noise in the duct and an algorithm in the controller seeks to minimize the noise detected at the error microphone.

Although ANC has been applied in three-dimensional spaces successfully (Gulyas et al., 2002), the simplest applications of ANC methods are in enclosed linear spaces, such as ducts, where the noise source can produce standing waves. The standing waves are essentially one-dimensional problems and can be attacked easily (Bies and Hansen, 2003). The highest achievable frequency for a standing wave is related to the largest cross-sectional dimension of the duct. For instance, if the duct is 110 by 120 mm, the widest cross-sectional dimension is the diagonal 163 mm. The highest frequency that can be expected to set up a standing wave is the wavelength divided by four ($\gamma/4$). So the shortest wavelength would be (40 × 163 mm = 651 mm). Given the speed of sound in air of 344 m/s, the highest frequency would be (344 m/s/0.651 m = 528.3

Table 1 — Noise dosimeter settings.

Parameter	Dosimeter 1	Dosimeter 2	Dosimeter 3
Weighting	A	A	A
Threshold level	90 dB	80 dB	off
Criterion level	90 dB	90 dB	85 dB
Exchange rate	5 dB	5 dB	3 dB
Response	Slow	Slow	Slow
Upper limit	140 dB	140 dB	140 dB
Designation	MSHA permissible exposure limit	MSHA action level	Wide range

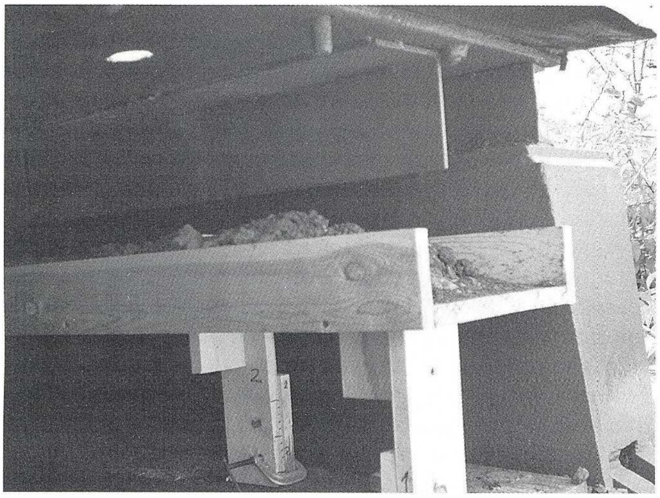

Figure 2 — Crusher end of stageloader section showing splitting vane and shelf loaded with coal.

Hz).

The height above coal in an operating stageloader typically varies erratically and unevenly from zero to 300 mm (12 in.) before the end of the gooseneck. The width of the two operating stageloaders and the test stageloader were all about 1.2 m (4 ft). Based on those dimensions, the maximum frequency for effective noise cancellation would be about 70 Hz, which is of little utility. As discussed below, the authors propose to divide the width of stageloaders into distinct channels using 135-mm- (5.3-in.-) high steel vertical dividers.

The study was divided into two phases. In the first phase, underground noise surveys were carried out at two different mines. In the second phase, ANC experiments were carried out on the aboveground non-operational stageloader modified by creating a vertical channel at the ceiling.

Methods and apparatus

The authors first investigated noise levels at two mines to characterize the noise levels, dose to the operators and operating parameters of two different stageloaders. The recorded stageloader noise was then used in active noise tests of a nonworking aboveground stageloader.

Underground stageloader noise surveys. Sound levels and noise dose data were recorded in ten surveys at two different mines. A Quest 2900 Octave Band Analyzer was used for sound levels and Quest Q-300 Noise Dosimeters were used for noise dose data. The Octave Band Analyzer was a Type II device calibrated before and after each survey with a Quest QC-10 Calibrator (Quest Technologies Inc., Oconomowoc, Wisconsin). The noise dosimeters were single-microphone, three-channel devices that were capable of applying three criteria, level/threshold level/exchange rate schemes, to logged data. The dosimeters were set to log the average level minute-by-minute. The dosimeter schemes are listed in Table 1.

For this study, the authors investigated exposures with two very different stageloaders. The first was a Joy stageloader and crusher assembly that was being used for a 2.4-m (7.9-ft) seam in the mid-Atlantic region (Pittsburgh seam). It was 41.8 m (137 ft) long and 1.22 m (4.00-ft) wide and was running at 126 m/min (413 fpm). The second was a DBT America stageloader and crusher assembly used for a 2.0-m (6.6 ft) seam in the Mid-Atlantic region. It was 21.3 m (70-ft) long and 1.20 m (3.9 ft) wide and was running at 128 m/min (420 fpm). This paper hereafter refers to the longer Joy model as the "long" stageloader and the shorter DBT as the "short" stageloader.

Active noise cancellation. Recorded underground mine noise was reproduced into an 8.5-m (28-ft) section of stageloader. The stageloader machine is a duct with an air space that varies, but under normal operation was described by the operators and observed by the authors as roughly 152 mm (6 in.) in height all across the width of the stageloader. The short stageloader width was approximately 1.2 m (3.9 ft). This means that the highest frequency controllable by ANC would be (344 m/s)/(4 × 1.21 m) = 71 Hz, which is much too low to be useful. Hence, for ANC to be used effectively, it is necessary to reduce the apparent width of the stageloader. A typical technique to reduce a dimension in a duct for ANC application is to insert splitting vanes down the length of the duct so that the duct is split into several smaller channels. In this case, to limit the airspace above the coal inside the stageloader so that higher frequencies could be controlled, a 135-mm vertical vane was added down the length of the section (see Fig. 2).

Also, a wooden shelf was constructed inside the stageloader and covered with loose coal to simulate the coal level in a working stageloader. These modifications together created a 170-mm- (6.7-in.-) wide by 135-mm- (5.3-in.-) high channel (see Fig. 2) with a gap all down its length if the shelf height was set lower than the height of the bottom of the vane. The 170-mm- (6.7-in.-) wide channel would theoretically allow creation of standing waves up to 377 Hz.

Three parameters were selected for investigation. The first parameter is shelf height, which dictates the cross sectional area of the channel and, if the height of the shelf is lower than the bottom of the vane, determines the height of the gap all along the length of the channel (see Fig. 2). The gap potentially would reduce the effectiveness of noise cancellation. It was important to the study because a practical vane may have to be short enough that such a gap between the vane and the top of the coal would exist at least part of the time. For this study, the gap in the channel was set either flush with the vane, 135 × 170 mm (5.3 × 7.0 in.) in cross section, or sloped from 205 mm (8-in.) after the crusher to 135 mm (5.3 in.) (i.e., no gap) 2 m (6.6 ft) in the direction of the tail.

The second study parameter was the distance between the reference microphones and the control speakers. The longer the distance the better the standing wave and the more time the system has to process the reference signal and counter it. On the other hand, operational constraints in the mine could limit the distance. Hence, it is important to understand the effects of this distance.

The third parameter was the number of references microphones, controls speakers and error microphones used. Some initial tests seemed to indicate that having two independent systems operating on the same noise increased the frequency range that could be controlled and, therefore, reduced the overall noise level further. Therefore, two systems were evaluated, one using a 2 x 2 x 2 (2 reference microphones, 2 control speakers and 2 error microphones) feed-forward ANC system, and the other a 1 x 1 x 1 system.

The recorded stageloader noise was random and broadband in frequency content. The EZ-ANC II Active Noise Controller (Causal Systems Inc., Adelaide, Australia) was used to analyze the recorded noise and generate the countering signals. Coherence of the reference and error microphones was judged by comparing the frequency response of the microphones to the same signal. The system was also found to be sufficiently "causal." Causality refers to the fact that the reference microphones picked up the noise of concern rather than the control speaker noise. This was attained by inserting the reference microphones into two 1.22-m- (4-ft-) long microporous plastic tubes (Model X5305, Porex Corp., Fairburn, Georgia), so that they were directed toward the source noise.

The reference and error microphones were placed directly in the channel and were isolated from vibration with 40-mm- (1.5-in.-) thick foam. The control speakers were placed outside of the channel with the speaker face centered on an opening into the channel. A separate microphone located with the error microphones fed the final noise to an OR-38 Real-Time Analyzer (OROS Inc., Dulles, Virginia) for instantaneous analysis. The relative position of the speakers and microphones are shown in Fig. 3.

All microphones were calibrated with a QC-20 Calibrator (Quest Technologies, Oconomowoc, Wisconsin) before and after the trials. Background noise was monitored during each trial to ensure it was at least 10 dB below the reduced levels in the frequency bands of concern.

The ANC device was allowed to stabilize for at least one minute before establishing weighting values for the frequency spectrum based on a random noise model. The OR-38 then recorded a 30-second sample and the average 1/n octave sound levels were recorded with ANC on and off.

A factorial experiment was conceived with two shelf heights (H), i.e., flush with coal 170 × 135 mm (7 × 5.3 in.) or sloped from 170 × 205 mm (7.0 × 0.8 in.); two systems (S), i.e., single or dual; and three microphone distances (D), i.e., 4.67, 6.24 and 8.33 m (15.3, 20.5 and 27.3 ft). Two repetitions were performed and all trials were randomized except the shelf height, which was difficult to adjust. All 12 trials were performed on one shelf height, then the shelf height was adjusted and the next 12 performed.

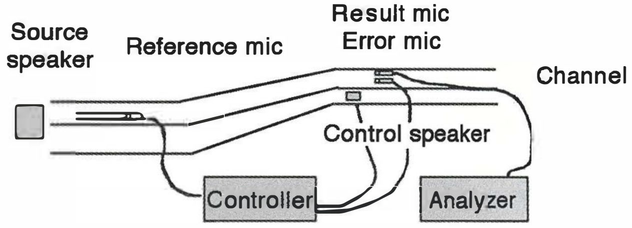

Figure 3 — ANC test apparatus

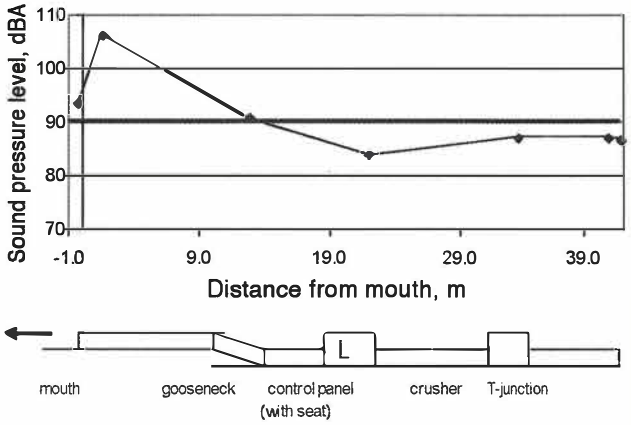

Figure 4 — Noise levels (dBA) along the long stageloader

Results

Underground stageloader noise surveys. The operator of the long stageloader could have been exposed to anywhere from 84 to 106 dBA (Fig. 4), depending on where the operator spent most of his time. Fortunately, he spent nearly all of his time at the control panel seat and was therefore exposed to the relatively low levels at that location, giving him a dose of 44%. His minute-by-minute exposures are shown in Fig. 5.

The operator of the second stageloader could have been exposed to anywhere from 90 to 98 dBA (Fig. 6). Because this stageloader was shorter, no location along its length was far enough from the main noise sources of the crusher, headgate drive and tail drive, to be as low as the long stageloader. This stageloader had no seat and the operator spent much of his

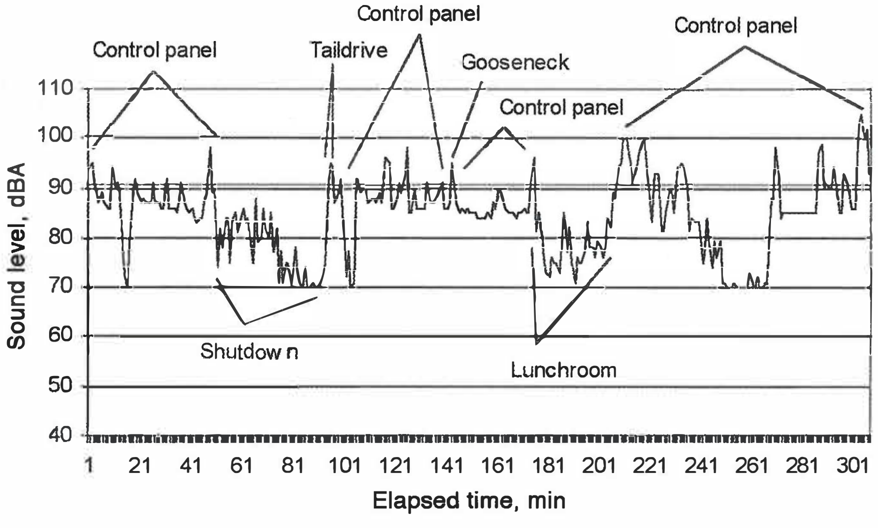

Figure 5 — Minute-by-minute noise level exposure to long stageloader operator.

Table 2 — Average 8-hour noise dose for headgate operators at long and short machines.

Occupation	n	Geometric mean dose	Geometric standard deviation
Headgate, short SL	5	103.1%	1.47
Headgate, long SL	4	23.3%	1.79

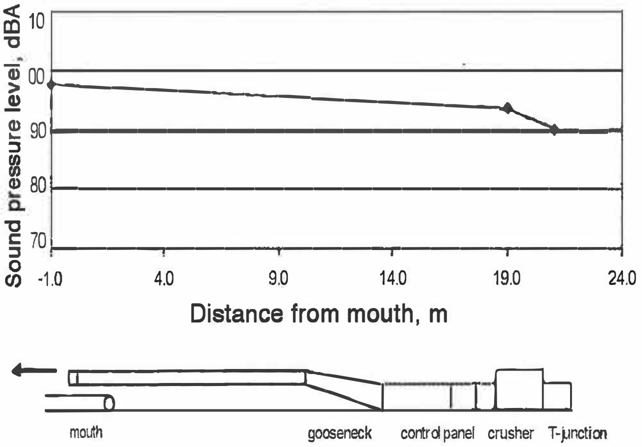

Figure 6 — Noise levels (dBA) along the short stageloader

time at the noisy control panel/crusher/headgate drive area next to the T-junction. The stageloader machine is the primary noise source for the operator's exposure. His minute-by-minute exposures are shown in Fig. 7.

MSHA noise dosimetry data from 2000 to 2004 for the headgate operators at the two mines are listed in Table 2. A two-sample, two tail t-test assuming unequal variances performed on the log-transformed data indicate that these two groups are significantly different (p = 0.0137).

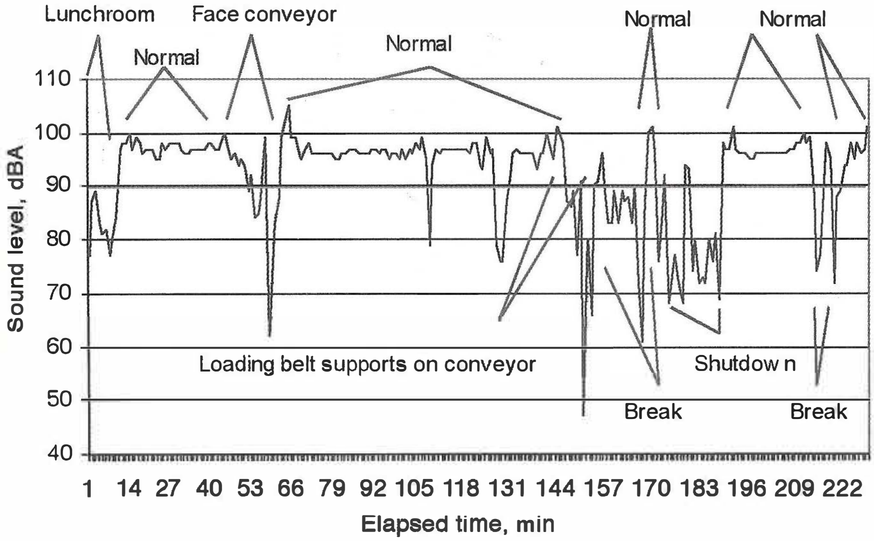

Figure 7 — Minute-by-minute noise level exposure to short stageloader operator.

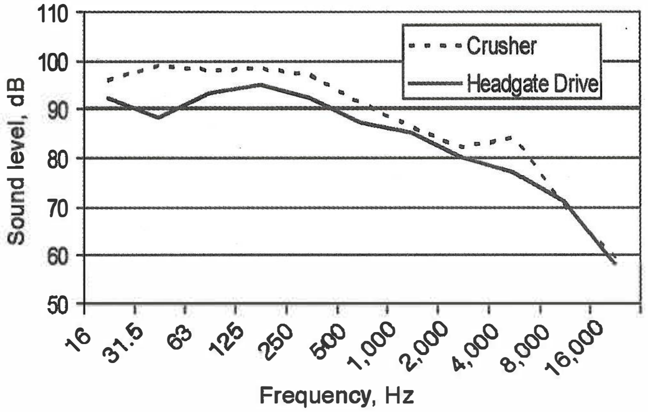

Figure 8 — Short stageloader frequency spectrum for crusher and headgate drive locations

For this reason, the short stageloader was selected for noise-control investigation. The noise frequency spectra for those areas where the operator spent most of his time are presented in Fig. 8.

A significant amount of sound energy was present below 1,000 Hz. Observing the higher of the two, i.e., the crusher noise, it is apparent that the noise in the octave bands below 1,000Hz contribute 92 dBA to the overall 94 dBA average value. Indeed, a 10 dB reduction at each octave band below 1,000 Hz would reduce the overall level to 90 dBA.

Active noise control results. All ANC results were analyzed using the statistical analysis software JMP (SAS Institute Inc., Carey, North Carolina). An analysis of variance (ANOVA) was run on the additive linear model of the three independent variables and their effect on the noise reduction (NR) of the recorded noise (Table 3).

The overall model was very nearly significant (p = 0.0509). Both shelf height and dual vs. single system were found to be not significant (p = 0.7655 and p = 0.4359, respectively), and they were removed from the model. Microphone distance was significant at p = 0.0085. When the noise reduction was modeled on microphone distance alone, the results were significant (p = 0.0065) and are given in Table 4. The simplified model was based on microphone distance alone (see Table 4).

Interaction among the variables was nonsignificant (p = 0.13 to 0.73) with the exception of the interaction of shelf height and system (p = 0.0194). However, the overall model was less significant (p = 0.0204) than the simple model in Table 4, so interaction terms were removed. The most significant model remained the linear model based on microphone distance alone. The reduction by microphone distance is given in Table 5 in A-weighted and unweighted decibels.

A typical unweighted frequency spectrum for the recorded stageloader noise before and after ANC is shown in Fig. 9. The noise was largely low frequency, so the ANC system focused on that portion of the noise.

Discussion

Given the average reduction by frequency for the best performing microphone distance, i.e., 8.33 m (27.3 ft), and the crusher noise of the short stageloader, the resultant overall noise level would be 91 dBA (Table 6). While this level would not be at or below 90 dBA, the operator could remain in the area for 418 minutes (roughly 7 hours) with the crusher operating continuously before reaching 100% dose. Expected dose for a continuous 8-hour exposure would be 115%, below the 132% citation threshold used by MSHA (MSHA, 2001).

The potential success is limited by the fact that the noise reduction would occur downstream of the microphone, so that the miner would only benefit if he or she were standing at least 9 m (30 ft) downstream of the crusher. However, using ANC technology in conjunction with passive controls may be promising. If passive controls reduce the noise in the walkway around the crusher and control panel but channel the noise down the airspace above the coal in the stageloader, then the ANC system could reduce the channeled noise. This combination of controls may be able to effectively reduce noise levels at all work areas for the headgate operator.

Table 3 — ANOVA of noise reduction model with all variables.

Model: $NR_{ijkl} = \mu + H_i + S_j + D_k + \varepsilon_{ijkl}$

Source	Degrees of freedom	Sums of squares	Mean squares	F-statistic	P-value
Model	3	30.70	10.23	3.08	0.0509
Shelf height (H)	1	0.30	0.30	0.09	0.7655
System (S)	1	2.10	2.10	0.63	0.4359
Microphone distance (D)	1	28.30	28.30	8.52	0.0085
Error	20	66.44	3.32	–	–
Total	23	97.15	–	–	–

Table 4 — ANOVA of linear model based on microphone position only.

Model: $NR_{ij} = \mu + D_i + \varepsilon_{ij}$

Source	Degrees of freedom	Sums of squares	Mean squares	F-statistic	P-value
Model (Microphone distance, D)	1	28.30	228.30	9.04	0.0065
Error	22	68.85	3.13	–	–
Total	23	97.15	–	–	–

Table 5 — Noise reduction by microphone distances.

Microphone distance	Unweighted (linear) Average ± standard deviation (dB)	A-weighted Average ± standard deviation (dBA)
4.67 m	4.3 ± 1.5	4.2 ± 1.1
6.24 m	4.8 ± 1.6	5.4 ± 1.3
8.33 m	6.9 ± 2.2	7.0 ± 2.2
Overall	5.3 ± 2.1	5.5 ± 1.9

Conclusions

Active noise-control technology has long been used for noise in duct problems. It has been successfully demonstrated here in an application on the stageloader for longwall mining. ANC could potentially yield a 7-dBA reduction in stageloader noise. Its application could be relevant when combined with traditional passive noise-control techniques to reduce headgate operator noise dose. Further research is needed to resolve practical difficulties in implementation, including mounting techniques to protect the microphones and speakers, robustness and simplicity of system operation and intrinsic safety issues. The microphones and control speaker should be mounted in protective steel boxes above the stageloader with a membrane, air curtain or some other method to keep the system clean of dust and moisture while still allowing sufficient air pressure fluctuation to respond properly. The boxes would have to be mounted in a section of the stageloader that was not prone to hitting the roof when uneven floor causes the stageloader to tilt. The ANC control system should be mounted in an explosion-proof box with electrical barriers applied to the input and output lines in order to comply with intrinsic safety standards. Lastly, the control system would have to be tested for vibration tolerance and insulated accordingly. Figure 10 displays the mounting concept for the stageloader.

It should be reiterated that even simpler controls, such as relocating the headgate operator to quiet areas, could be a more effective strategy for noise dose reduction, as demonstrated by the headgate operator at the long stageloader in this study. The operator's tendency to remain close to the seat at the control panel insured that his exposure to noise was below 100% of the allowed dose.

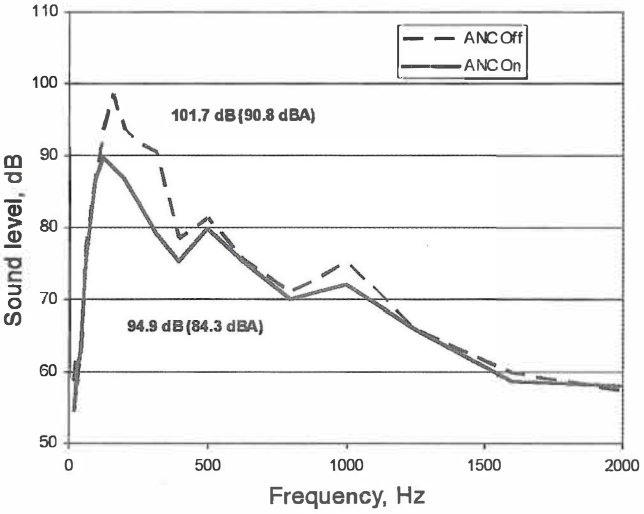

Figure 9 — Typical frequency spectrum of stageloader noise before and after ANC

Table 6 — Potential reduction of short stageloader noise by ANC using best microphone position.

Frequency Hz	Average reduction at microphone distance, 8.33 m (27.3 ft)	Resultant stageloader crusher noise level, dB	A-weighted result, dBA
31.5	0	99.0	59.6
63	0	98.0	71.8
125	3	95.2	79.1
250	10.2	86.8	78.2
500	3	88.0	84.8
1,000	0	86.0	86.0
2,000	0	82.0	83.2
4,000	0	84.0	85.0
8,000	0	70.0	68.9
		Overall:	91

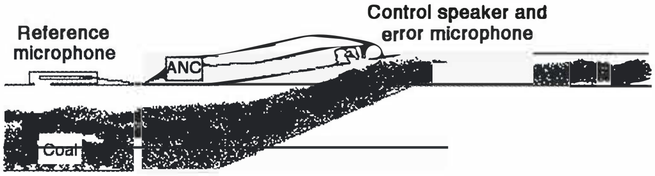

Figure 10 — Mounting concept for ANC on a stageloader

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