Determining Underground Roof Bolting Machine Operators Noise Exposure Using Laboratory Results

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ABSTRACT

Mine Safety and Health Administration (MSHA) data indicates that the roof bolting machine is third among all equipment and second among equipment in underground coal mining whose operators exceed the MSHA-PEL (Mine Safety and Health Administration-Permissible Exposure Limit). In response to this, the National Institute for Occupational Safety and Health (NIOSH) has conducted a study to reduce overexposures of noise to operators of roof bolting machines. An important segment of the research is to determine, characterize and measure sound power levels radiated by a roof bolting machine during different drilling configurations. The determined sound power levels generated during the drilling cycle are of major interest because the levels represent the overall sound power generated by the machine. These sound power levels, determined from laboratory tests, can be used to accurately assess the effectiveness of proposed controls for reducing noise exposure to roof bolting machine operators. By using the sound power level results obtained from the laboratory and a commercially available acoustical modeling package, a method for predicting sound pressure levels to roof bolting machine operators for differing drilling types and parameters could be determined. This paper provides a method for predicting sound pressure levels at the operator's position of a roof bolting machine in an underground coal mine using sound power levels determined in the laboratory. To determine validity, underground coal mine data was also collected to compare predicted and measured sound pressure levels. The results of the predicted sound pressure level data were the same as the underground measured results. This research will provide the mining industry with a valid method for predicting a roof bolting machine operator's noise dosage underground given any type of drilling configuration or drilling method utilized from laboratory testing.

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1. INTRODUCTION

Noise is one of the most pervasive health hazards in mining. NIOSH identified occupational noise-induced hearing loss (NIHL) as one of the ten leading work-related diseases and injuries. Mine Safety and Health Administration coal noise sample data (Title 30 CFR, Part 62) collected from 2000 to 2002 show that 65% of the equipment whose operators exceeded 100% dosage comprise only seven different types of machines: auger miners, bulldozers, continuous miners, front end loaders, roof bolters, shuttle cars (electric) and trucks (MSHA, 2000-2002). In addition, the MSHA data indicate that the roof bolter is third among all the equipment and second among equipment in underground coal mines whose operators exceed 100% dosage[1,2].

NIOSH is addressing this at the Pittsburgh Research Laboratory (PRL) to reduce noise exposure to roof bolter operators in coal mining. This paper concentrates on determining the sound power noise emissions during the drilling cycle of a roof-bolting machine. Laboratory sound power measurements were collected and through the utilization of an acoustic model, an operator's noise exposure or dosage could then be determined. This research effort will provide the mining industry with the opportunity to predict noise dosage to roof bolting machine operators without the laborious effort of conducting numerous underground measurements.

2. BACKGROUND

Underground mining machines are subject to many variables that can affect the noise levels. Some of these variables cannot be controlled while others can be influenced or even controlled by the machine operator. The acoustic environment in which the mining machines operate is a critical factor affecting the sound pressure levels. Underground mines are enclosed areas, which usually represent diffused sound fields. An ideal diffuse sound field is a sound field in which the time average of the mean-square sound pressure is everywhere the same and the flow of acoustic energy in all directions is equally probable. The geometry and the composition of the surfaces influence the overall sound level by the way sound waves (treated as rays in the acoustic model) are reflected or absorbed.

Mine entries also have various shapes, rectangular, square, or arched, and various dimensions as well. These variations in shape and size affect the overall sound energy that is reflected or absorbed. These are the variables that cannot be controlled in the acoustic environment, and include geometry and composition of the surfaces, shape of the mine opening, and the compressive strength of the affected medium.

A methodology and model was developed to predict sound pressure levels at the operator position of a roof bolting machine using full-octave band frequency measurements obtained from laboratory and in-mine testing. The objective was to determine a miners' effective noise dosage related to measured and determined engineering noise control tests determined from laboratory trials dependent upon full-octave band sound power levels. Upon completion of the model, the measured sound power determined in the laboratory, with a calculated or predicted sound absorption coefficient, was then entered into the model to determine an operator's noise dosage relative to the drilling cycle of the roof bolting machine. To achieve this, an acoustic modeling program based on ray-tracing techniques was utilized to predict the steady-state sound pressure level and the associated sound decay in a mine environment. The information then provided a snapshot of the environment and calculated the noise levels throughout the environment.

Ultimately, this effort is providing the mining industry with a method to model a simple event within a mine section and determine the noise dosage of the roof bolting machine operator.

3. APPROACH

Equation 1 can be used to relate the sound power of the noise source to the sound pressure level. This equation is a function of the directivity of the source, the distance from the source, the geometry and absorption of the environment. Listed below is the equation:

$$L_p = L_w + 10 \, \mathrm{Log}_{10} \left[(Q / 4\pi r^2) + (4(1-\alpha) / S\alpha) \right] + 10.3, \qquad (1)$$

where

L_p = sound pressure at a distance r from the source
L_w = sound power level of source
Q = directivity of the source
r = distance from the source
S = surface area
α = average absorption coefficient

If the directivity, the distance, and the geometry and absorption of the environment are kept constant the equation shows that the sound pressure level is directly proportional to the sound power level. By knowing this, a commercially available software package, Raynoise[3], can be used to show how the sound power relates to sound pressure level at a given point with a known geometry and absorption coefficient. The only requirements for Raynoise are octave sound power levels, octave absorption coefficients, room or entry dimensions, and measurement locations in x, y, and z coordinates.

Because of all the variations, both geometrically and acoustically in underground mines it would be difficult to measure sound power in these conditions and achieve constant test results. It would be impossible to control the acoustic environment, which would make it difficult to evaluate the roof bolting machine and its components for noise levels. Therefore, sound power testing was conducted in the Pittsburgh Research Lab (PRL) NVLAP accredited reverberation chamber. This allowed sound power measurements to be determined in a controlled acoustic environment and independent of variables of underground mines. The PRL reverberation chamber (Illustration 1) was designed for sound power testing of large equipment in conformance with ISO 374.[4] The chamber meets ISO 374 in the frequency range of 100Hz to 10,000 Hz.

Illustration 1: PRL reverberation chamber

Once the sound power level of the roof bolting machine is determined, the other requirements necessary for sound level prediction are the absorption coefficients, the characteristics of the specific roof bolting machine, room or entry dimensions, and measurement locations in x, y, and z coordinates. The sound absorption coefficients used for this research were determined by past NIOSH research[5]. The height measurement of 1.52 m was selected because this distance, on average, represents the average ear-height of an individual. The three measurement locations were chosen based on the operator's working locations. Finally, research results have shown the dominant noise sources of a roof bolting machine are the drill bit, the drill steel, and the drill chuck[6]. These noise sources correspond to three points on a line source extending from the bit to the chuck, with the drill bit/contact surface as one source, the drill steel another and the third source being the drill chuck.

4. LABORATORY TEST PLAN

Two Fletcher roof bolting machines were tested, a Roof Ranger II and a HDDR. A test apparatus for holding the drilling medium was located in the rear of the reverberation chamber (Illustration 1). The machine position in the reverberation chamber was chosen, due to the length of the machine. The only location requirements for both the test apparatus and the roof bolting machine were they be a minimum distance of 1.5 m from any wall or ceiling and at least 1 m from the microphones. Also, the machine should be placed asymmetrically in the chamber according to the ISO 3741 standard, section 7.2[7]. Since, the machine cannot be operated remotely only one operator is allowed in the reverberation chamber during testing. This person must wear dual hearing protection, both ear plugs and ear muffs.

In formulating a conservative test plan for testing, it was decided to use drilling components and parameters that were representative of industry usage. The roof bolting machine was tested using 2.54 cm and 3.49 cm carbide bits both vacuum and wet, a 1.22 m drill steel either hex or round, and under varying loading conditions. These loading conditions were accomplished by varying the thrust pressure and rotation speed. Also, three different media for drilling were used, which would provide a wide range of penetration rates with respect to noise.
Given these parameters two different size drill bits, two different type drill bits, two types of drill steel, three different drilling media, five rotation speeds for each thrust pressure, and five different thrust pressure were considered for each media. Also, each test was conducted using three different drilling methods (vacuum, mist, and drilling). This resulted in a total of 900 sound power tests that were conducted.

The individual test data collected (900 tests) from the research effort was then compiled and summarized into a matrix for drilling into the three compressive strength media tested (soft-41.368 MPa, medium-117.211 MPa, or hard-165.473 MPa). This would be used to determine overall sound power levels given any type of drilling method (vacuum, wet or mist) and using varying types of drilling parameters or configurations related to thrust, rotational speed, bit size and shape of drill steel.

5. COMPARING SOUND PRESSURE LEVELS –UNDERGROUND MEASUREMENT RESULTS VS RAYNOISE RESULTS

Sound pressure level measurements were conducted at the operator position of a Fletcher Roof Ranger II roof bolting machine in an underground coal mine. The underground mine height varied from approximately 1.22 to 1.52 m and the thickness of the coal seam varied from 81 -102 cm. The mine operator provided the opportunity to measure sound pressure levels relative to two bolting machines utilizing a vacuum system and mist system drilling method respectively. The roof bolting plan for the section is shown in illustration 2.

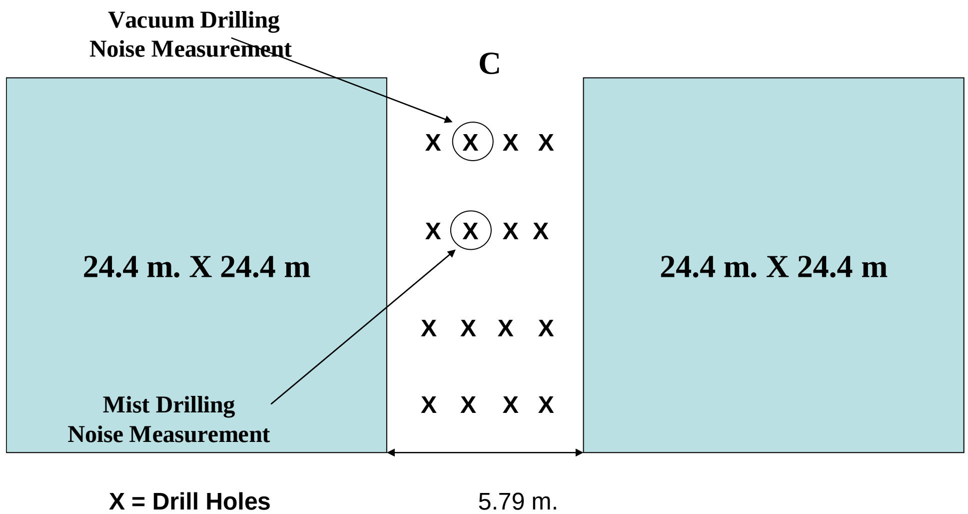

Illustration 2: Roof bolting plan

Each roof bolting machine utilized a 2.54 cm drill bit, hex drill steel and drilled to a depth of 1.52 m into the immediate roof. The roof consisted of a highly fractured shale rock consistent of a rock type with a low compressive strength (approximately 41.368 MPa. The drilling configurations for both machines were set at a rotational speed of 500 rpm and a thrust of approximately 6.5 kip. Sound pressure level measurements were conducted at the operator position of each machine. Table 1, illustrated below provides the results of the sound pressure level testing.

Table 1: Underground test results

Operation of roof bolting machine	Roof Ranger II (vacuum) dB(A)	Roof Ranger II (mist system) dB(A)
Idling	82	82
Mist system on No idling	NA	88
Drilling	101	96

The sound pressure levels experienced at the operator position during drilling utilizing the vacuum system of drilling was 101 dB(A). Utilizing a mist system type of drilling, the operator was exposed to a sound pressure level of 96 dB(A), resulting in a 5 dB(A) difference in sound pressure level.

The next step was to utilize the Raynoise program to compare the measured underground sound pressure level experienced at the operator position to the predicted sound pressure level determined thru Raynoise.

The input parameters used for Raynoise were based on the underground measurement conditions and operating parameters. The underground rock media had a compressive strength-41.368 MPa and the sound power was based on a Roof Ranger II vacuum drilling with a hex drill steel, 2.54 CM bit, rotational speed of 500 rpm, and a thrust setting of 6.36 kip. Table 2 gives the sound power levels used based on this information. The other input parameters used for the Raynoise program are listed in Table 3.

Table 2: Sound power levels results for a roof bolting machine drilling into a media of 6,000 psi at operating parameters of 500 rpm rotation speed and a thrust of 6,363 lbs using a 2.54 cm bit and hex drill steel.

Octave-band (Hz)	Sound Power Level dB
63	85.6
125	89.4
250	101.1
500	96.5
1000	97.4
2000	103.3
4000	103.7
8000	97.1

Table 3: Other input parameters used for the Raynoise program

Entry absorption coefficients (octave band): .03 .04 .2 .14 .15 .19 .28 .45
Entry dimensions: 1.83 m H x 5.79 m W x 24.38 m L
Measurement points 1.52 m above floor. (Operator's position locations designated by the numbers 1, 2, & 3. Illustration 4)
1 Line source on LEFT boom approx. 1 m long from chuck to roof entry point.

Illustration 3 displays the Raynoise sound pressure level contours, along with the A-weighted sound pressure levels based on the input parameters of tables 2 and 3.

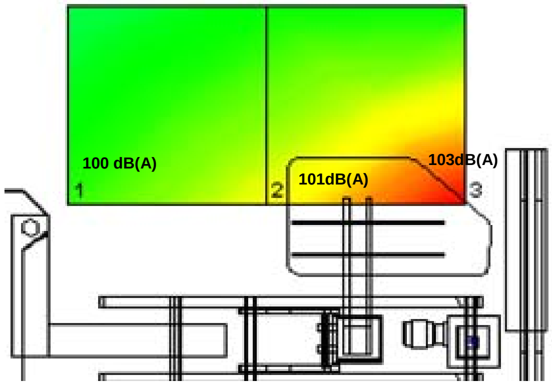

Illustration 3: A Raynoise sound pressure level contour for a roof bolting machine.

Table 1 data provided a sound pressure level of 101 dB(A) at the operator position of the roof bolting machine from underground measurements. The location of the measurement underground was the same location as measuring point number 2 utilized for Raynoise, Illustration 3. The determined or predicted sound pressure level using Raynoise was 101 dB(A), the same sound pressure level as measured underground. It should be noted, in order for Raynoise validation, data was collected in an actual underground mine environment. Due to mine accessibility, characterization of the acoustic environment, along with measuring sound pressure levels associated with operators of roof bolting machines occurred in a mine with low compressive strength rock media during drilling operations. However, the research effort has proven that by measuring laboratory sound power level results of the roof bolting machine given any compressive strength rock media, along with proper characterization of the acoustic and geological environment underground, one could predict the sound pressure level experienced by a roof bolting machine operator with confidence.

This research would provide the mining community with an approach, which utilizes sound power levels acquired from laboratory tests and measured absorption coefficients from underground testing to accurately predict or determine sound pressure levels, at any location in a mine section. The next section will demonstrate and provide an approach for determining the noise dosage of a roof bolting machine operator utilizing the predicted or determined sound pressure levels obtained from Raynoise.

6. DETERMINING NOISE DOSAGE OF A ROOF BOLTER OPERATOR FROM PREDICTED SOUND PRESSURE

The noise dosage a worker receives can be expressed by the following equation:

$$Dose\% = (100/TC)[\int_0^{RTime} 2^{(LS-CL)/ER}\,dt], \tag{2}$$

and

$$Dose\% = (100/TC)(2^{(LS-CL)/ER})[\int_0^{RTime} dt], \tag{3}$$

Therefore

$$Dose\% = (100/TC)(2^{(LS-CL)/ER})(RTime), \tag{4}$$

where

Dose% = workers' noise dosage, percent
TC = criterion time, 8 hours or 28,800 seconds

LS = Sound pressure level, dB(A)
CL = Criterion level, dB(A)
ER = Exchange rate, dB(A)
RTime = Run time, seconds

Using the equation above, with a predicted or determined sound pressure level at the operator position of a roof bolting machine, the machine operators' noise dosage could then be determined. For instance, if we use the example illustrated in section 5, where the compressive strength of the rock media was 41.368 MPa and the roof bolting machine operator utilized the vacuum drilling method, with a 1-inch bit, hex drill steel, a rotational speed of 500 rpm and a thrust setting of 6.36 kip, the measured and validated predicted sound pressure level was determined to be 101 dB(A) at the operator position of the machine. Using the above equation, the mining community can then determine the operator's noise dosage, relative to the MSHA-Permissible Exposure Limit (MSHA-PEL) (90 decibels, A-weighted, as an 8-hour time-weighted average [90 dBA as an 8-hr TWA]), with a 5 dBA exchange rate) or the NIOSH-Recommended Exposure Limit (NIOSH-REL) (85 decibels, A-weighted, as an 8-hour time-weighted average [85 dBA as an 8-hr TWA]), with a 3 dBA exchange rate received per drilling an individual hole during the drilling cycle of the roof bolting machine as shown below:

$$Dose\% = (100/TC)(2^{(LS-CL)/ER})(RTime) \qquad (5)$$

where

TC = 28,800 seconds
LS = 101 dBA
CL = 90 dBA
ER = 5 dBA
RTime = 50 seconds
(based on a penetration rate of 3.05 cm/sec and a hole depth of 1.52 m)

Therefore, the dose percentage of the roof bolter operator for this particular example would be 80%. Additionally, assuming similar rock media (compressive strength of 41.368 MPa) and the operator of the roof bolting machine drilling 78 drill holes per shift for installation of roof bolts, the operator's noise dosage relative to only utilizing the roof bolting machine for drilling would be:0.8% x (78 drill holes) = 62.4 % of the MSHA-PEL of 100%. In comparison, the NIOSH-REL noise dosage for the same situation mentioned above would be 546%, based on a criterion level of 85 dB(A) and an exchange rate of 3 dB(A). Table 4 provides the noise dosage of a roof bolter operator (per hole and per shift), relative to a respective sound pressure level and based on a run time of each hole consisting of 50 seconds and assuming the operator will drill 78 holes per his working shift.

Table 4: Noise Dosage (MSHA and NIOSH) of Roof Bolting Machine Operator

Sound Pressure Level dB(A)	Run Time (sec/hole)	MSHA-Dose (%/hole)	NIOSH-Dose (%/hole)	Holes Drilled per Shift	MSHA-Dose (%/shift)	NIOSH-Dose (%/shift)
85	50	0.0	0.2	78	0.0	13.5
86	50	0.0	0.2	78	0.0	17.1
87	50	0.0	0.3	78	0.0	21.5
88	50	0.0	0.3	78	0.0	27.1
89	50	0.0	0.4	78	0.0	34.1
90	50	0.2	0.6	78	13.5	43.0
91	50	0.2	0.7	78	15.6	54.2
92	50	0.2	0.9	78	17.9	68.2
93	50	0.3	1.1	78	20.5	86.0
94	50	0.3	1.4	78	23.6	108.3
95	50	0.3	1.7	78	27.1	136.5
96	50	0.4	2.2	78	31.1	172.0
97	50	0.5	2.8	78	35.7	216.7
98	50	0.5	3.5	78	41.1	273.0
99	50	0.6	4.4	78	47.2	343.9
100	50	0.7	5.6	78	54.2	433.3
101	50	0.8	7.0	78	62.2	546.0
102	50	0.9	8.8	78	71.5	687.9
103	50	1.1	11.1	78	82.1	866.7
104	50	1.2	14.0	78	94.3	1091.9
105	50	1.4	17.6	78	108.3	1375.7
106	50	1.6	22.2	78	124.4	1733.3

This approach has provided the mining community with a way to predict sound pressure levels, with relative certainty, at the operator position of a roof bolting machine and at differing locations within a mine section, utilizing laboratory testing results relative to the roof bolting machine. Additionally, the mining community was presented with an approach to characterize the noise dosage a roof bolting machine operator will receive, based on laboratory results. This will provide the mining industry with the opportunity to predict sound pressure levels and noise dosage to machine operators without the laborious effort of conducting numerous underground measurements.

7. CONCLUSIONS

NIOSH researchers conducted sound pressure level measurements at the operator position of a Fletcher Roof Ranger II roof bolting machine in an underground coal mine and the results provided a sound pressure level of 101 dB(A). When comparing the results to the Raynoise program the results were the same as the operator's position. The research effort has proven that laboratory sound power level results could predict with confidence the sound pressure level experienced by a roof bolting machine operator.

In general, given any type of drilling method (vacuum, wet or mist), rock media (compressive strength), drilling parameters or configurations related to thrust, rotational speed, bit size and shape of drill steel for roof bolting machines, sound power levels can be determine from the laboratory data. Utilizing the sound power data with Raynoise the sound level of the operator could be determined, which could be used to determine the noise dosage to machine operators from drilling. This research will provide the mining industry with a valid method for predicting a roof bolting machine operator's noise dosage underground given any type of drilling configuration or drilling method utilized from laboratory testing.

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