Application of a microphone phased array to identify noise sources on a roof bolting machine

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ABSTRACT

Exposure to excessive noise over time can cause permanent hearing loss. Workers in the mining industry are frequently exposed to A-weighted sound levels in excess of 90 dB. The A-weighted sound level at the roof bolter operator's location can exceed 100 dB while drilling. The National Institute for Occupational Safety and Health (NIOSH) measured the sound pressure at the roof bolter operator's position and utilized a phased array of microphones with beamforming software to identify noise sources on a roof bolting machine while drilling. The test data indicates the sound level at the operator's position is dominated by the 2000 Hz through 5000 Hz one-third-octave-band sound levels. The beamforming results indicate that the drilling noise is primarily from two areas: the portion of the drill steel just below the rock and the drill steel-chuck interface. This paper will discuss the methods used to identify the primary noise sources.

1. INTRODUCTION

In 1996, NIOSH published the National Occupational Research Agenda, which identified hearing loss as the most common job-related disease in the United States.[1] Approximately 30 million workers are exposed to hazardous sound levels alone or to hazardous sound levels in conjunction with ototoxic agents.[2] Despite more than 30 years of noise regulation in the mining industry, mine workers develop hearing loss at a significantly higher rate compared to the non-noise exposed population. An analysis of audiograms conducted by NIOSH in 1996 shows that by the age of 50, nearly 90% of coal miners had a hearing impairment.[3] In contrast, only 10% of those who are not exposed to occupational noise experienced a hearing loss by the same age.

In 1999, the Mine Safety and Health Administration (MSHA) modified its rules regarding noise exposure in an effort to reduce the occurrence of noise-induced hearing loss.[4] Rather than relying solely on hearing protection devices, MSHA's new rule requires mine operators to use all feasible engineering and/or administrative controls to reduce the noise exposures of overexposed miners'. However, for many machines, such as a roof bolter, noise controls that reduce the

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operator's noise exposure below the MSHA Permissible Exposure Level (PEL) are not currently available.

When measuring noise exposure, NIOSH recommends using a criterion level of 85 dB(A) with a 3-dB exchange rate[5] whereas the MSHA PEL uses a criterion level of 90 dB(A) with a 5-dB exchange rate.[4] Between 2000 and 2005, MSHA made 6215 measurements of roof bolter operators' noise exposures. Of these measurements, 1086 exceeded the MSHA PEL.[6] Furthermore, in the coal industry, roof bolter operators accounted for 17% of all the noise exposures that exceeded the PEL. The overall A-weighted sound level at the roof bolter operator's location often exceeds 100 dB when drilling. At this sound level, a roof bolter operator would reach MSHA's PEL after 2 hours and NIOSH's Recommended Exposure Level (REL) after 15 minutes. To reduce roof bolter operators' noise exposures, noise controls must be developed that target the dominant noise sources during drilling. Determining the dominant source(s) of roof bolter drilling noise is the focus of this paper.

A roof bolter is a large electrically-powered machine used to stabilize the mine roof after coal has been extracted. The roof bolter is used to drill holes into the mine roof using 25 to 35 mm diameter drill bits attached to drill steels with either hexagonal or round cross-sections. The lengths of the drill steels vary from approximately 0.3 meters to 1.5 meters, or longer, depending on the mine and its roof conditions. After a hole is drilled, a roof bolt is inserted into the drilled hole to connect the overlying strata, thereby supporting the roof. To spread the load across the roof, roof bolts are sometimes inserted through a steel plate prior to inserting the bolt into the roof. Figure 1 shows a roof bolter in an underground coal mine. Figure 2 shows a hexagonal drill steel, a round drill steel, and two drill bits.

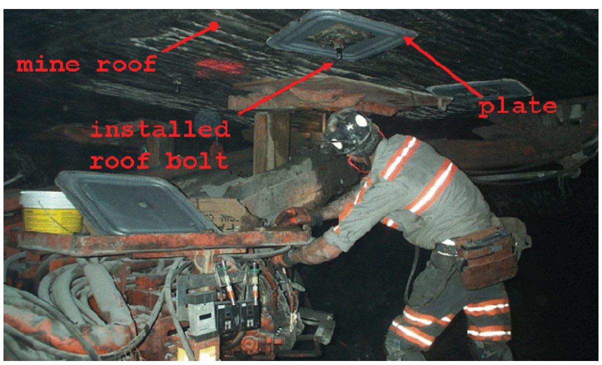


Figure 1: A roof bolter in an underground coal mine.

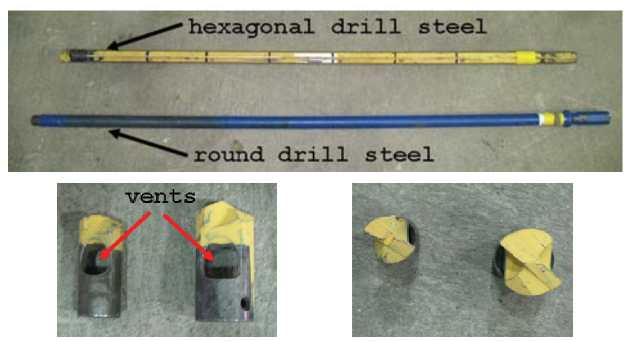


Figure 2: hex and round drill steels for a 35-mm diameter drill bit (upper) and two examples of drill bits (lower).

2. TEST SETUP AND INSTRUMENTATION

All testing was performed using a Fletcher model HDDR roof bolter in the NIOSH Pittsburgh Research Laboratory (PRL) hemi-anechoic chamber (see Figure 3). An overhead view of the PRL hemi-anechoic chamber is shown in Figure 4. A test fixture constructed of welded steel tubes was used to support the material to be drilled. Some of the tubes of the test fixture were filled with sand to reduce vibration of the test fixture to minimize fixture-radiated noise. The fixture was positioned approximately 3.7 meters from the end and 2.4 meters from the left side of the hemi-anechoic chamber walls. C-channels welded to the fixture enable the material to be cantilevered over the fixture which allows a clear view of the interface between the material and the drill steel. Granite blocks were used as the material for all tests because prior experience has shown that using granite reduces test-to-test variability. The granite block was held in place using chains that are tensioned with ratcheting chain binders. Rubber strips were used between the block and the fixture and a urethane sheet was placed between the chains and the block to minimize noise radiated by the chains and fixture.

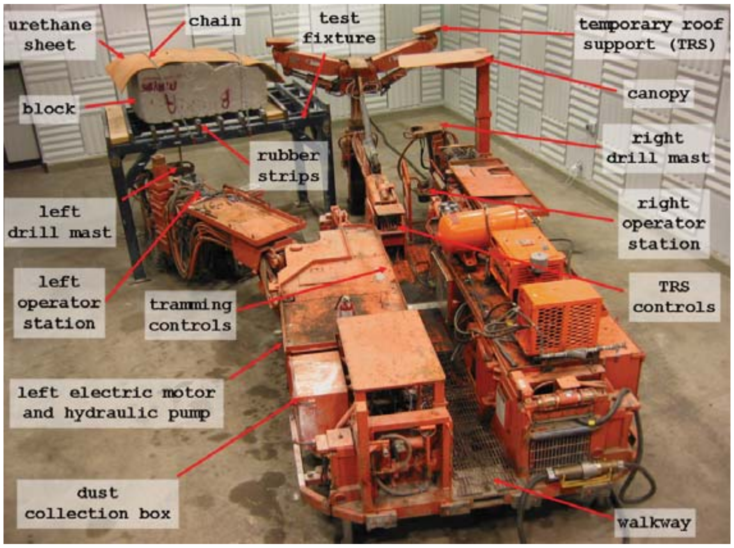


Figure 3: Fletcher HDDR in the PRL hemi-anechoic chamber.

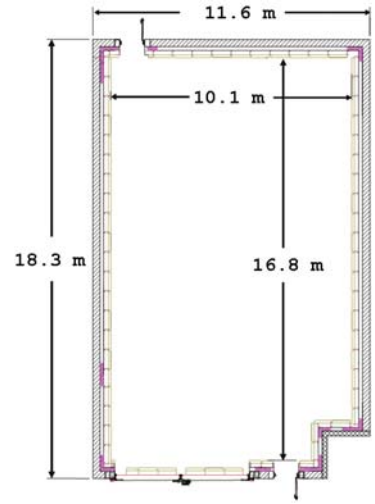
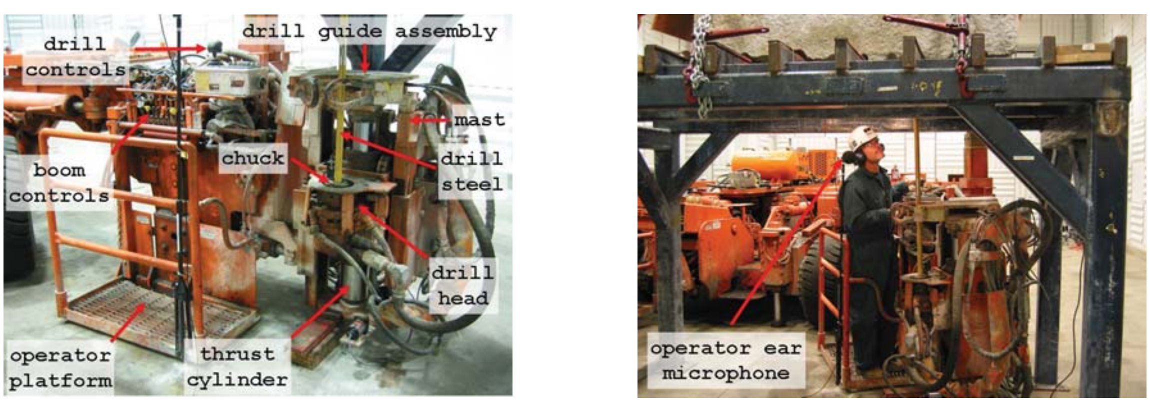


Figure 4: Overhead view of the PRL hemi-anechoic chamber.

The HDDR, which is approximately 8 meters long and 3 meters wide, uses two 37.3-kW AC motors to propel the machine and to operate the drilling apparatus which is powered by hydraulic pumps and motors. The HDDR has two drilling stations so two operators can drill holes and install roof bolts simultaneously. To drill a hole, a drill steel is inserted into the chuck on the drill head and a bit is attached to the top of the drill steel. The operator then positions the drilling apparatus and sets the thrust and rotation rate. For this machine, the cuttings from drilling are collected by a vacuum system through vent openings in the bit (refer to Figure 2), down the drill steel, which is hollow, and into the dust collection box located at the rear of the machine. The potential sources of noise during drilling include the electric motors, hydraulics, vacuum system, and drilling apparatus. Figure 5a shows the operator's platform and drilling apparatus and Figure 5b shows the operator at the controls. While drilling, the operator is approximately 1 m from the drill steel.



(a) (b)

Figure 5: Operator station, drilling apparatus, and controls (a) and operator at controls under text fixture (b).

Two data acquisition systems were used for data collection: an LMS Pimento and a Bruel & Kjaer Pulse. The LMS Pimento data acquisition system was used to measure the sound pressure at the operator's ear using a Bruel & Kjaer 4188 microphone and the drill steel rotational speed using an optical sensor. The recorded sound pressure was post-processed to calculate the A-weighted one-third-octave-band sound level spectra. Noise source identification was performed using beamforming.[7] For this application, beamforming is more appropriate than sound intensity[8] and near field acoustic holography[9] because drilling noise contains significant content up to about 5000 Hz and the data must be acquired simultaneously due to movement of the drill and test-to-test variability. To collect the beamforming data, the Pulse data acquisition system was used to simultaneously record the sound pressures using a 42-microphone wheel array (see Figure 6). The on-axis spatial resolution for this array for several measurement distances is shown in Figure 7. The data from the array was post-processed using Bruel & Kjaer's Beamforming application.

Figure 6: NIOSH 42-microphone beamforming array.

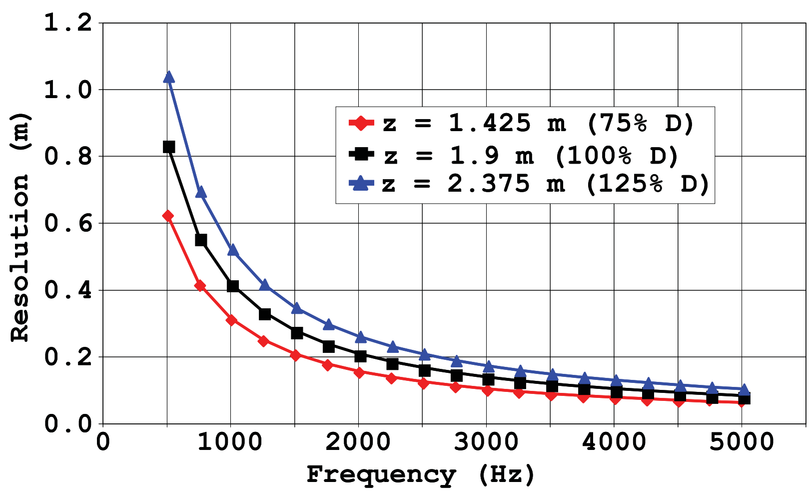


Figure 7: Spatial resolution of the NIOSH beamforming array for measurement distances of 1.425 m, 1.9 m, and 2.375 m.

3. TEST PROCEDURES

The HDDR was positioned so the left drilling apparatus was beneath the test fixture (refer to Figure 3). The desired rotational speed and thrust were set using an automatic control system. To eliminate the effects of drilling with a dull bit, a new drill bit was used for each hole.

The sound pressure at the operator's ear was recorded (refer to Figure 5b) for the following conditions:

- Electric motors and hydraulics operating without drilling
- Electric motors, hydraulics, and vacuum system operating without drilling
- Electric motors, hydraulics, and vacuum system operating with drilling.

The recordings without drilling were used to determine the contributions of the electric motors, hydraulics, and vacuum system to the overall A-weighted sound level at the operator's ear while drilling, which requires the operation of these components. A 35-mm diameter drill bit and a 1.2-meter long hexagonal drill steel were used for these tests. Each recording was a minimum of 15 seconds in length. The resulting drilling data were examined to determine when the drill steel rotational speed stabilized. The sound pressures for each measurement were post-processed to calculate the A-weighted sound levels in one-third-octave bands. For the sound pressure recorded while drilling, only the data after the rotational speed stabilized were post-processed to maintain consistency. The post-processed data for each drilling test was approximately 10 seconds in length due to the time required for the rotational speed to stabilize.

To identify noise sources, sound pressures were recorded and post-processed using the NIOSH beamforming array with the Bruel & Kjaer Pulse. The array was positioned 2.4 meters in front of the drill head. Holes were drilled using a 35-mm diameter drill bit and either a 1.2-meter long hexagonal drill steel or a 1.5-meter long round drill steel. The rotational speed and thrust were set at 200 RPM and 28.3 kN, respectively. These values were used because they are representative of commonly used settings. Once again, the rotational speed of the drill steel was measured with an optical tachometer. After the rotational speed stabilized, which took only a few seconds, the sound pressures were recorded for 2.5 seconds. The data was then post-processed with the Bruel & Kjaer beamforming software using 1-second long clips to compute the one-third-octave-band sound pressure levels across multiple grid points located on a plane which encompassed the drilling apparatus. In the beamforming software, the source plane distance was set to 2.4 meters and free field was selected as the measurement condition. Each set of data was processed immediately after collecting the data using a 2.2 meter wide by 1.6 meter high grid with a spacing of 0.10 meters. After reviewing the results, the data was reprocessed to improve the spatial resolution using a 0.3 to 0.4 meters wide by 1.6 meters high grid with a spacing of 0.05 meters.

4. TEST RESULTS AND DISCUSSION

A. Operator Ear Measurements with Hexagonal Drill Steel

Prior to examining the results of the beamforming calculations, it is important to gain an understanding of the frequency content and sound level at the operator’s ear. The beamforming results provide good information on the noise radiated toward the array. However, the noise radiated toward the operator may have different frequency content. Therefore, an analysis of the sound pressure at the operator’s station was performed.

Figure 8 shows the A-weighted one-third-octave-band sound levels at the operator’s ear with the electric motors and hydraulics operating and also with the electric motors, hydraulics, and vacuum system operating. The data indicate that the overall A-weighted sound level is below 75 dB without the vacuum system operating and 90 dB with the vacuum system operating. Since the levels are more than 10 dB different, the electric motors and hydraulics are insignificant in terms of the overall A-weighted sound level for the second measurement. Figure 9 shows the A-weighted one-third-octave-band sound levels at the operator’s ear while drilling a hole into the granite block with a 35-mm diameter bit and a 1.2-meter long hexagonal drill steel with the rotational speed and thrust set to 200 RPM and 9.4 kN, 400 RPM and 9.4 kN, and 200 RPM and 28.3 kN. The overall A-weighted sound levels of these measurements were 102.6 dB, 107.8 dB, and 109.1 dB, respectively. Each set of drilling data shows a hump in the one-third-octave-band spectra from about 1250 Hz to 10 kHz. Furthermore, the 2000 Hz through 5000 Hz one-third-octave bands have the highest in-band levels for each case. An important observation is that the frequency content does not change much with increasing rotational speed or thrust while the levels increase significantly with increasing rotational speed or thrust.

Figure 10 shows the A-weighted one-third-octave-band spectra with the electric motors, hydraulics, and vacuum system without drilling overlaid with the data measured while drilling with a rotational speed of 200 RPM and a thrust of 28.3 kN. The most significant changes occur at and above the 1250 Hz band. The in-band A-weighted sound levels increase by more than 10 dB for each of these bands. The largest increase, about 25 dB, occurs in the 4000 Hz band.

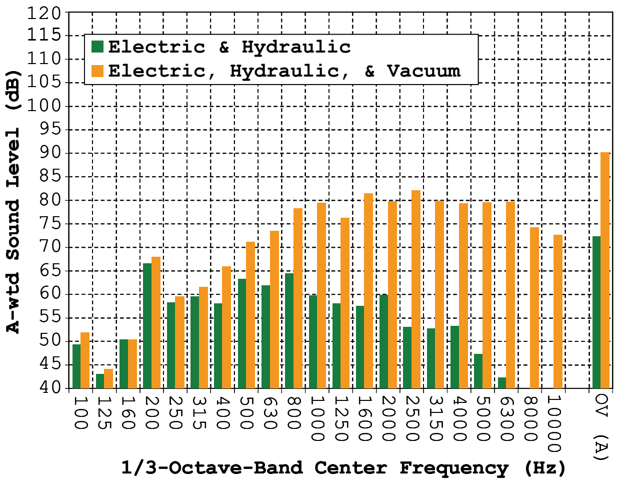


Figure 8: Operator ear A-wtd 1/3-octave-band sound levels with the electric motors and hydraulics and with the electric motors, hydraulics, and vacuum system.

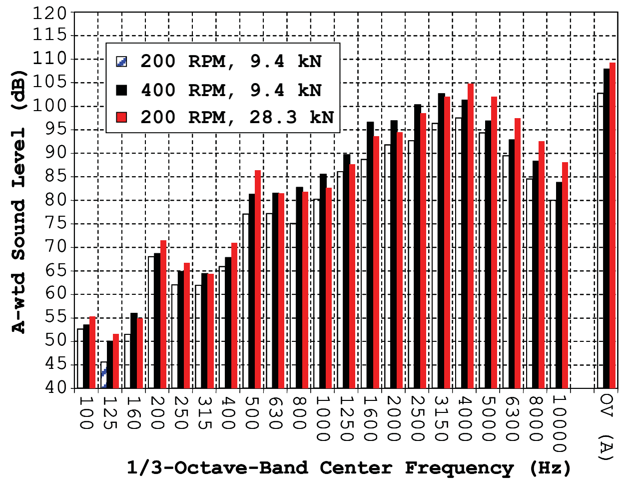


Figure 9: Operator ear A-wtd 1/3-octave-band sound levels while drilling into granite with a 35-mm diameter bit and a 1.2-meter long hexagonal drill steel.

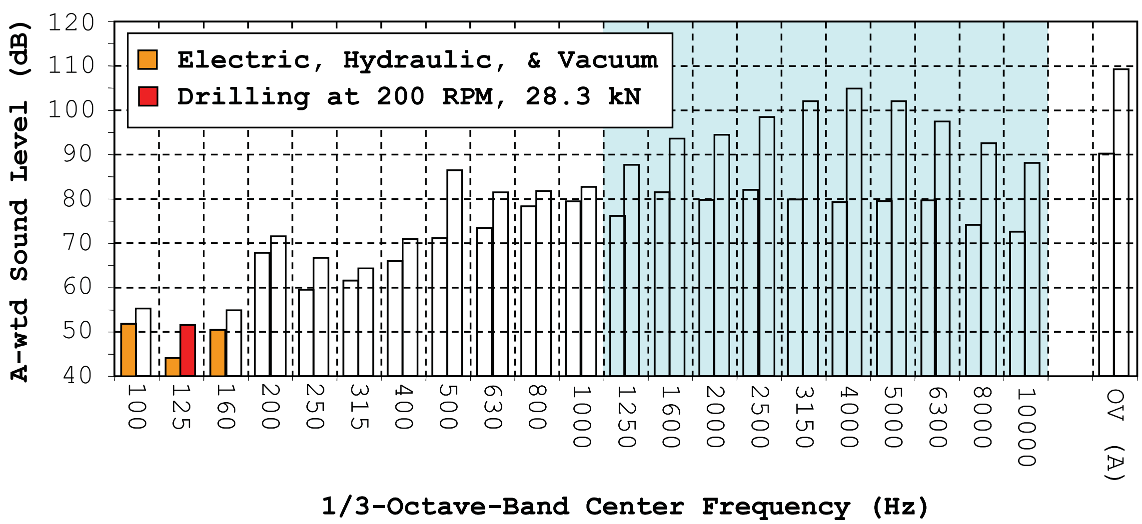


Figure 10: Operator ear A-weighted one-third-octave-band spectra with the electric motors, hydraulics, and vacuum system without drilling and for drilling with a rotational speed of 200 RPM and a thrust of 28.3 kN.

To reduce the sound level at the operator's ear while drilling, noise controls must be developed that target the noise generating mechanisms that are responsible for the high frequency drilling noise. Prior to designing these controls, it is necessary to determine the components that are the most significant sources of drilling noise. One possible source is fracturing of the rock at the bit-rock interface. In addition, the drill steel may radiate noise due to vibration from the cutting forces. However, due to the slenderness of the drill steel, it may not be an efficient radiator of noise. The drill head is another possible noise source. Forces at the bit-rock interface may be carried down the drill steel and transmitted into the drill head.

If the main source of noise is the bit-rock interface, noise controls would be limited to bit design, changes in drilling parameters, and barrier-type controls. If the noise is radiated by the drill steel and/or the drill head, application of isolation and damping techniques may reduce the radiated noise. Barriers or partial enclosures around the drill steel and drill head may also be effective at reducing noise. However, barrier-type controls for the drill steel may be unacceptable to the bolter operator.

B. Beamforming Results for Small Drilling Depth using Hexagonal Drill Steel

The first recordings using the beamforming array were collected using a 35-mm diameter drill bit and a 1.2-meter long hexagonal drill steel. The recording started as soon as the rotational speed became stable. This required only a few seconds. With drill settings of 200 RPM and 28.3 kN, the penetration rate was roughly 10 mm/sec. So, the rotational speed would stabilize prior to reaching a depth of 50 mm. When collecting data with the beamforming application, the picture is automatically taken immediately prior to recording the sound pressures. Only the first second of data was processed to minimize smearing of the contour plots due to movement of the drill. Since the drill moved roughly 10 mm during 1 second, this effect is insignificant.

Figure 11 shows the contour plot for the 2500 Hz through 5000 Hz one-third-octave bands for the first test. This figure is from the results of processing the data at the beginning of a hole with a depth of a few centimeters immediately after the test using a grid spacing of 0.1 meters. The data processed was collected at the beginning of a hole with a depth of a few centimeters. The box around the perimeter of the figure indicates the boundary of the calculation grid and the dots represent the calculation locations. The red dot corresponds to the grid point yielding the highest level in the 4000 Hz one-third-octave band. The one-third-octave-band spectrum for this grid location is shown in the lower left corner of the figure and the average one-third-octave-band spectrum for all grid locations is shown in the lower right corner. The frequency content of the noise radiated toward the array is dominated by the 4000 Hz one-third-octave band, which is the largest contributor to the operator ear sound level with the same rotational speed and thrust (refer to Figure 10). In addition, there appears to be a hump in the spectrum at and above 1600 Hz, similar to the spectrum of the sound pressure at the operator's ear. The figure shows the largest contribution to the noise radiated toward the array originates near the top of the drill steel. In addition, there appears to be a secondary source near the bottom of the drill steel. The top source could be from the drill steel, the bit-rock interface, or both. The bottom source could be from the drill steel, the drill head, or both.

Several additional measurements were performed with the same rotational speed and thrust to gain a better understanding of the noise sources. Near the top of the drill steel, the contour appears to be shifted slightly toward the C-channel used to support the rock. This effect could be due to sound reflecting off the C-channel. In addition, the cross-tube behind the drill steel is another surface that could reflect sound and alter the contour map. Neither of these reflective surfaces would be present under real-world conditions in a mine. To reduce the effects of these reflective surfaces, 25-mm thick acoustic foam was affixed to the C-channels and cross-tube and the measurements were repeated. The bottom surface of the block may also be a significant reflector of noise. Reflection of sound off the block would tend to shift the contour toward the block which makes it difficult to determine if the noise is generated by the drill steel or the bit-rock interface. Therefore, a layer of 25-mm thick acoustic foam was attached to the bottom of the block and a third measurement was performed. Even though attaching foam to the bottom of the block would reduce the reflection from the block, noise generated from the bit-rock interface would still be able to emanate from within the hole. To determine if significant noise is generated at the bit-rock interface, a fourth test was performed with a layer of barrier-foam on the bottom of the block instead of the layer of acoustic foam. If the bit-rock interface is a significant source of noise, the results would show a change in the levels and, possibly, the source location near the top of the drill steel.

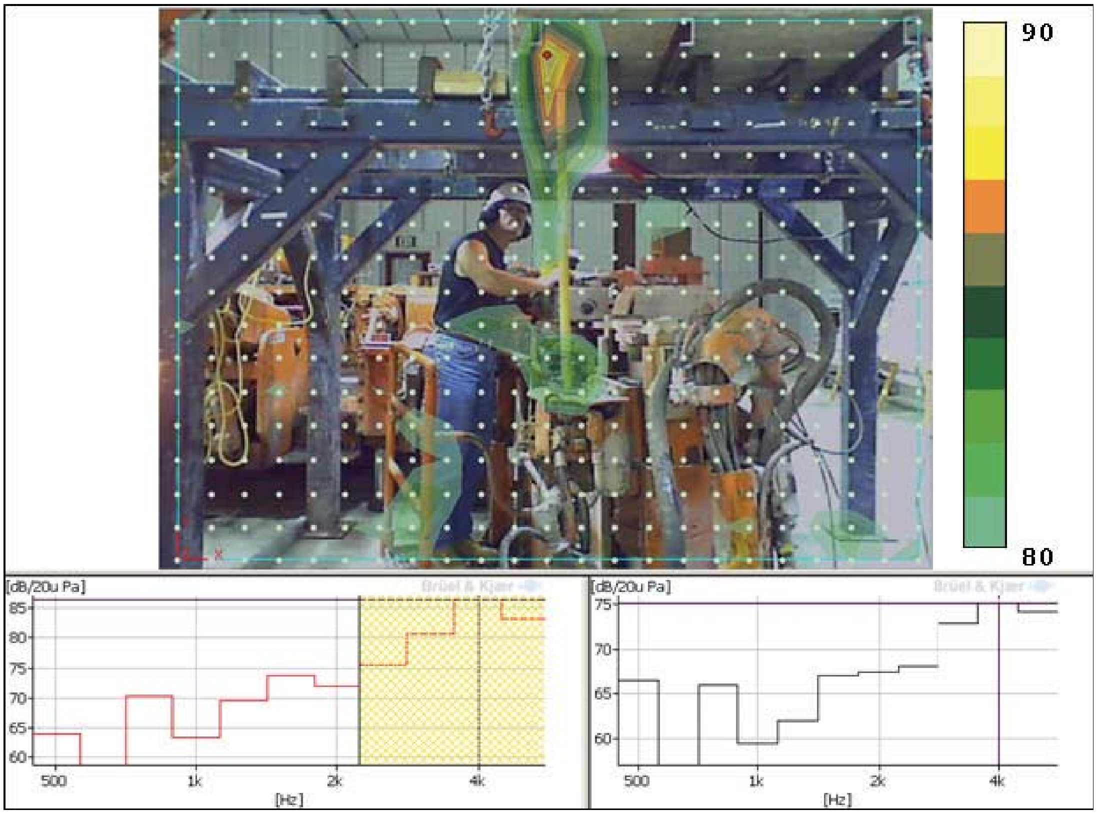


Figure 11: Beamforming results with 35-mm dia. drill bit and 1.2-m long hex drill steel for RPM and 28.3 kN.

Figure 12 shows the contour map for the first measurement with (a) no treatments, (b) with the C-channels and cross-tube treated with acoustic foam, (c) with the C-channels, cross-tube, and bottom of the block treated with acoustic foam, and (d) with the C-channels and cross-tube covered with acoustic foam and the bottom of the block covered with the barrier-foam. Each of these images show the results computed for the 2500 Hz through 6300 Hz one-third-octave bands using a grid spacing of 0.05 meters with a 0.3 to 0.4 meters wide by 1.6 meters high grid centered on the drill steel. Adding the foam to the C-channels and cross-tube appears to shift the high noise area at the top of the drill steel slightly so it is more centered on the drill steel (refer to Figures 12a and 12b). In addition, the portion of the drill steel directly in front of the cross-tube appears to radiate less noise due to reducing the reflection from the cross-tube. The high radiation area near the bottom of the drill steel also seems to be more significant since the noise radiated near the top of the drill steel was reduced. Adding foam to the bottom of the block slightly shifts the source at the top of the drill steel toward the chuck (see Figure 12c). The source at the top of the drill steel also appears to begin several centimeters down from the bottom of the block. Changing to barrier-foam on the bottom of the block (Figure 12d) appears to have no effect on the resulting contour plot. This result seems to prove that the noise near the top of the drill steel is due to radiation from the drill steel rather than from the bit-rock interface. The noise near the bottom of the drill steel may be radiated by the drill steel, the chuck, or both.

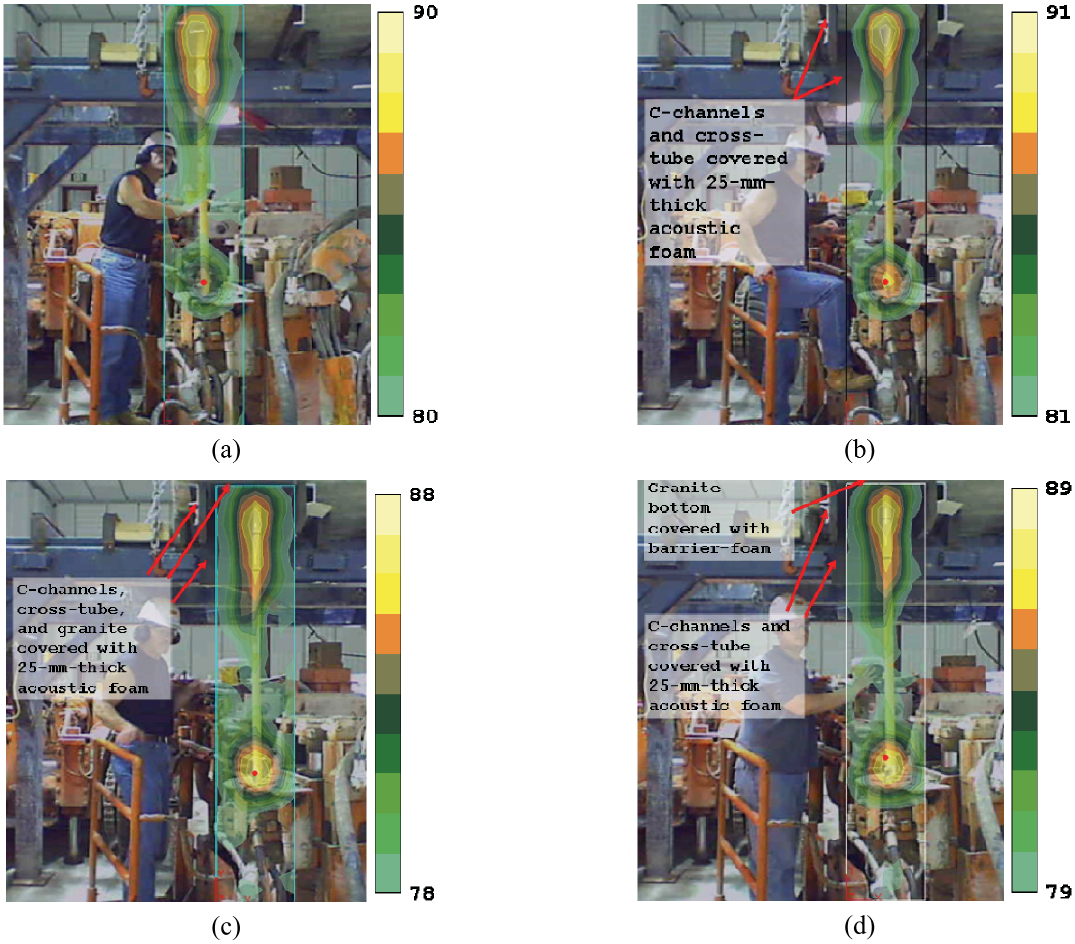
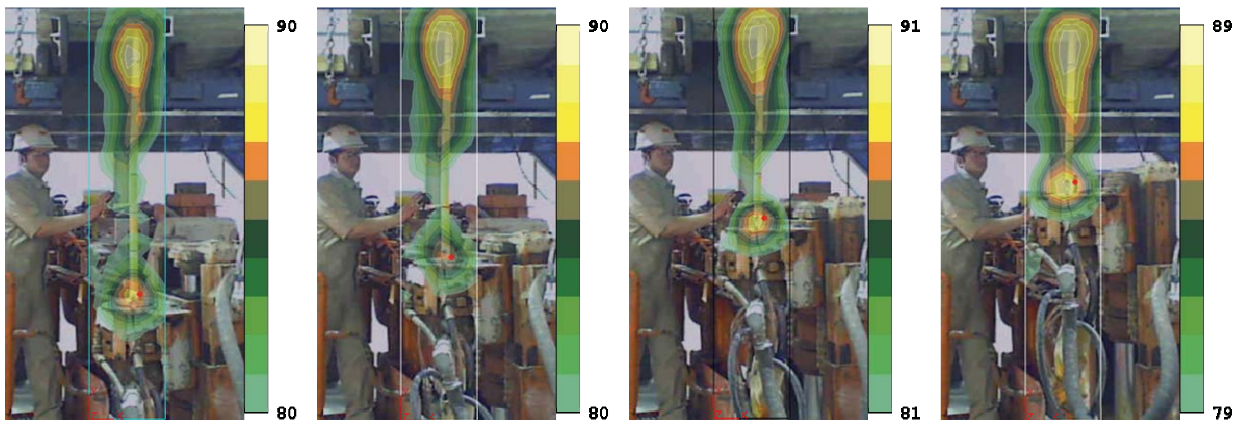


Figure 12: Beamforming results with 35-mm dia. bit and 1.2-meter long hexagonal drill steel for 200 RPM and 28.3 kN (a) std fixture, (b) 25-mm thick foam on C-channels and cross-tube, (c) 25-mm thick foam on C-channels, cross-tube, and bottom of block, and (d) 25-mm thick foam on C-channels and cross-tube and barrier-foam on bottom of block.

C. Beamforming Results for Increasing Drilling Depth

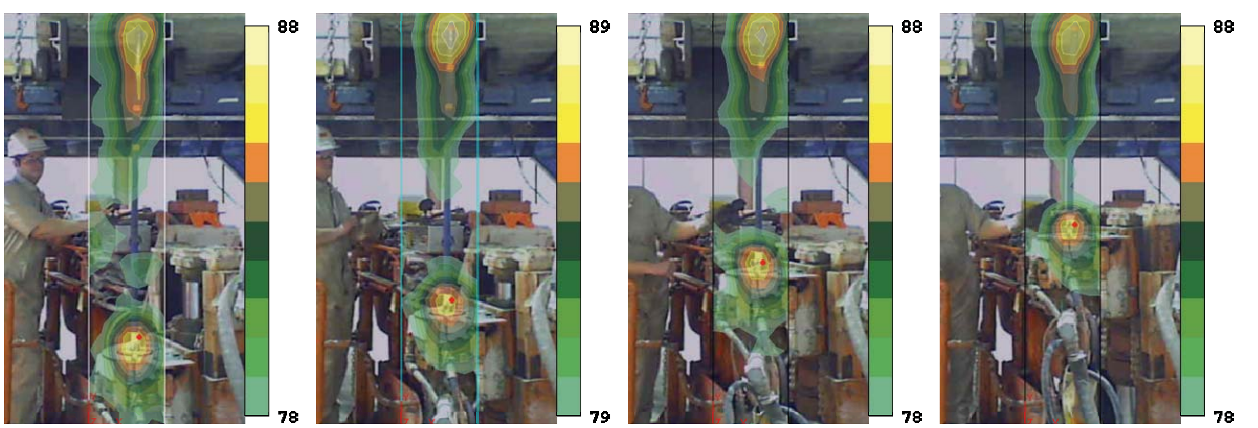
The previous measurements examined the radiation for only the first few centimeters of penetration into the rock. Two series of measurements were performed as a hole was drilled with a 35-mm diameter drill bit. Data were collected for depths of 0 cm, 0.15 cm, 0.30 cm, and 0.45 cm. A 1.2-meter long hexagonal drill steel was used for the first series of measurements and a 1.5-meter long round drill steel was used for the second series of measurements. All measurements were performed with 25-mm thick acoustic foam on the C-channels and cross-tube to reduce the influence of the test fixture. The foam was removed from the bottom of the block because under real-world conditions the reflection of sound from the bottom of the block is present. The foam may reduce the importance of the noise radiated from the top of the drill steel relative to the total noise. All measurements were performed with a rotational speed of 200 RPM and a thrust of 28.3 kN.

Figures 13 and 14 show the resulting contour plots for the 2500 Hz through 6300 Hz one-third-octave bands with a grid spacing of 0.05 meters for the 1.2-meter long hexagonal drill steel and the 1.5-meter long round drill steel, respectively. Each figure shows that as the penetration depth increases, the noise source near the top of the drill steel remains in nearly the same location. This may be due to the cancellation effect along the length of the drill steel as adjacent portions of the drill steel vibrate out of phase. At the onset of drilling the hole, there is no cancellation at the top of the drill steel. However, adjacent sections down the length of the drill steel tend to cancel one another. As the depth is increased, the portion of the steel just beneath the block is not cancelled but portions of the drill steel away from the block cancel the radiation from adjacent sections. The source near the bottom of the drill steel travels with the drill head. These results seem to indicate that the mechanisms of noise radiation are independent of drilling depth.



(a) (b) (c) (d)

Figure 13: Beamforming results for 1.2-m hex drill steel (a) start of hole, (b) 0.15 m, (c) 0.30 m, and (d) 0.45 m.



(a) (b) (c) (d)

Figure 14: Beamforming results for 1.5-m round drill steel (a) start of hole, (b) 0.15 m, (c) 0.30 m, and (d) 0.45 m.

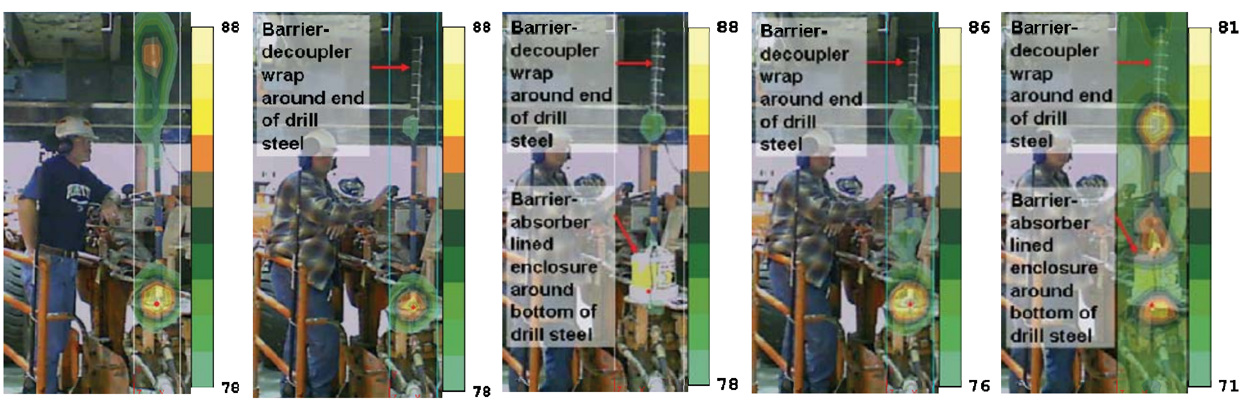
D. Beamforming Results with Trial Noise Treatments

Based on the results from prior measurements, it appears that two regions are responsible for the noise generated during drilling. Each contour plot shows the top portion of the drill steel as a region of high noise radiation. In addition, the interface between the bottom of the drill steel and the chuck seems to be a significant contributor to radiated noise. Noise controls that target these areas could significantly reduce the radiated noise.

To validate this presumption, a series of tests were performed with trial noise treatments applied to the top of the drill steel and the interface between the bottom of the drill steel and the chuck. A barrier with a foam decoupler was wrapped around the top of the drill steel and secured to the drill steel using nylon cable ties. To treat the drill steel-chuck interface, a barrier-absorber lined enclosure was used. A hole was placed in the top of the enclosure to enable the enclosure to be slid over the drill steel. The through-hole was sized to minimize the gap between the drill steel and the enclosure. A round drill steel was used to reduce the noise leaking through the gap between the drill steel and the enclosure.

Three tests were performed: (1) no treatments, (2) barrier-decoupler wrap at the top of the drill steel, and (3) barrier-decoupler wrap at the top of the drill steel and the barrier-absorber lined enclosure at the bottom of the drill steel. The C-channels and cross-tube on the fixture and the bottom of the granite block were treated with 25-mm thick acoustic foam for these measurements to reduce reflections from these surfaces. This makes the two areas of high noise radiation more obvious on the contour maps. Each test was performed with a rotational speed of 200 RPM and a thrust of 28.3 kN. Both beamforming and operator ear data was collected and post-processed for each test.

Figure 15 shows the contour maps for the results of the aforementioned series of tests in the 2500 Hz through 6300 Hz one-third-octave bands using a grid spacing of 0.05 meters. Figures 15 a, b, and c have the same range for the color bar to show the effects of the trial noise treatments whereas Figures 15 d and e are scaled to show the top 10 dB of noise sources to highlight the spots of high noise radiation with the treatments. Figures 15 b and c show the trial noise treatments substantially reduced the noise radiated at the top and bottom of the drill steel. Figures 15 d and e show that with the trial noise treatments the area of the drill steel just below the barrier-decoupler wrap is an area of high noise radiation. Moreover, Figure 15 e shows the leaks through the gap between the enclosure and the drill steel and at the interface between the enclosure and the chuck. The A-weighted sound levels at the operator's position corresponding to Figures 15 a, 15 b, and 15 c were 108.3 dB, 107.1 dB, and 102.9 dB, respectively.



(a) (b) (c) (d) (e)

Figure 15: Trial noise control tests - (a) baseline, (b) barrier-decoupler wrap at top of drill steel, (c) barrier-decoupler wrap at top of drill steel and enclosure at the bottom of the drill steel, (d) same as (b) with adjusted scale for color bar, and (e) same as (c) with adjusted scale for color bar.

5. CONCLUSIONS

The A-weighted sound level at the operator's station on a roof bolter used in coal mining typically exceeds 100 dB while drilling. When drilling into granite with a 35-mm diameter drill bit attached to a 1.2-meter long hexagonal drill steel in the laboratory, the A-weighted operator ear one-third-octave-band sound level spectrum is dominated by the 1250 Hz through 10 kHz bands. The 2000 Hz through 5000 Hz one-third-octave band have the highest levels in this instance. The results of beamforming measurements indicate that the majority of drilling noise is radiated by two areas: the portion of the drill steel just below the rock and the drill steel-chuck interface. This result is independent of drill steel type (e.g. hexagonal or round) and drilling depth. The beamforming results from tests with trial barrier-type noise treatments applied to the top of the drill steel and to the drill steel-chuck interface indicate that barriers may be a viable means of reducing roof bolter operators' noise exposures. Noise controls that isolate cutting forces from the drill steel or damp drill steel vibrations could also greatly reduce sound levels generated during drilling.

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