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Engineered noise controls for miner safety and environmental responsibility☆

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12.1 Background

Despite more than 30 years of noise exposure regulation (i.e., establishing and enforcing permissible exposure limits (PELs)), noise-induced hearing loss (NIHL) continues to be one of the most prevalent diseases in the mining industry. A recent study conducted by the National Institute for Occupational Safety and Health (NIOSH), in which over one million audiograms were analyzed, revealed that the mining industry has the highest prevalence in hearing loss among all other industries surveyed [1]. In fact, the mining sector has the highest prevalence of hazardous workplace noise exposures (76%) among all industrial sectors [2]. Despite engineering and administrative controls implemented to reduce noise, miners continue to exhibit a high prevalence (24%) of hearing difficulty [3]. Within the mining industry, underground coal miners are particularly at risk of noise overexposure due to confined environments in which they work and the close proximity of equipment operators to the mining machines they run. As a result, underground coal miners have the highest self-reported rate of hearing loss. In this context, there is a clear need to develop, evaluate, and implement effective noise controls for various pieces of equipment in order to reduce noise-induced hearing loss in the mining industry.

12.2 Approaches to noise control

In general, there are three approaches to reduce noise exposure levels encountered by miners: (1) controlling noise at the source by making physical changes that modify and attenuate the noise generation mechanism, (2) implementing noise controls in the transmission path between the noise source and the receiver; i.e., the miner, and (3) implementing noise controls at the receiver; i.e., personal protective equipment.

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The most preferred approach is the first approach—controlling noise at the source. However, this approach requires a thorough understanding of the noise-generating mechanism, and usually involves modifying this generation mechanism. For example, reducing the airflow speed from an aero-acoustically generated noise can result in significant noise reduction.

When noise control at the source is not possible, then noise controls in the transmission path should be considered. These controls usually have the form of acoustic enclosures absorbing some of the noise and/or isolating the noise source from the receiver (miner). It is very important that these enclosures are designed with heat transfer considerations in mind to prevent overheating of noise-generating components such as electric motors, gear boxes, etc. A drawback of acoustic enclosures in underground environments is the reduced visibility that they can cause, thus creating safety concerns.

Finally, personal protective equipment (PPE) such as ear muffs and earplugs should always be worn when noise levels are equal to or exceed 85 dB(A). A variety of styles and materials for hearing protection devices (HPDs) are commercially available with features that allow them to adapt to being worn with other PPE such as safety glasses and hard hats. Importantly, care should be exercised to guarantee proper fit and consistent wearing of these devices.

All HPDs have a noise reduction rating (NRR) on the packaging, which provides an estimated noise attenuation for that product when it is used correctly. However, although they will protect the worker from hearing damage due to noise, compliance credit is not given by the Mine Safety and Health Administration (MSHA) for their use. In other words, MSHA's rules for compliance do not permit subtraction of the HPD's stated NRR from the actual noise exposure level of the miner. Therefore, although HPDs may in theory reduce the noise reaching the ear of the miner, the employer is still responsible for reducing the noise exposure of that worker, as if HPDs were *not* being used. This is one reason why engineered noise control solutions are still needed despite the wide availability of HPDs.

12.3 Current technology

Advances in different areas of science and engineering provide specific tools that can be used to identify noise sources, develop noise controls, and evaluate solutions both in the laboratory and in underground environments. These advances in technology result in the availability of various types of tools and materials that can be used for purposes of noise control. This section presents some of these tools that have been successfully implemented and used to develop noise controls in the mining industry.

12.3.1 Engineering software for acoustics modeling

Small- and medium-sized mining machines are usually tested in hemi-anechoic and/or reverberation chambers to locate noise sources, and to determine sound power levels, respectively. However, for larger machines, it can be difficult or even impossible to conduct testing in such chambers due to the large dimensions of these machines relative to the dimensions of these chambers. In these cases, tests may have to be conducted in the field, and for mining equipment, this often means testing underground and in confined spaces. For large complex machines, test protocols may become quite complicated with a large number of measurements required. In some instances, it may not be possible to conduct measurements under actual operating conditions. Because of concerns about ignition sources, most acoustic measurement systems cannot be used at the working face of a coal mine. In such cases, modeling of machine dynamics and noise radiation may be the best approach.

Numerical models for dynamic and acoustic prediction constitute the most common means to conduct noise control development for different types of mining equipment. When numerical models of a significant sound-radiating component are created, the first step is to validate them using data obtained from experimental tests. This validation process guarantees that the models are an accurate representation of actual parts/components.

Once validated, numerical models can be used to explore various noise control alternatives readily. Therefore, some of the benefits of using these models involve increasing the efficiency of the process and reducing the cost incurred in the fabrication of physical prototypes that would have to be built and tested if these models were not available.

There are different methods to build these numerical models; however, the most commonly used are the boundary element method (BEM), the finite element method (FEM), and the hybrid finite element/statistical energy analysis (FE/SEA). It is not the purpose of this chapter to elaborate on each of these methods, but rather to provide an overview of the benefits and applicability of each of these methods in the mining industry, as described later. There is extensive literature that explains in detail each of these methods.

In acoustics, the boundary element method provides a way to solve the wave equation by discretizing the boundary and solving integral equations for each element that are mathematically equivalent to the original partial differential equation [4]. The main advantage of this method is that only the boundary of the domain needs to be discretized. This advantage is more significant when the domain is exterior to the boundary, such as in sound radiation and scattering problems. In terms of analysis frequency, the BEM constitutes an effective tool for low to mid frequencies (below 1000 Hz) due to discretization requirements. As a rule of thumb, six elements per wavelength are recommended when using the BEM in order to obtain acceptable results [5].

The finite element method also provides a way to solve the wave equation governing acoustic phenomena. In contrast to the BEM, this method requires that the entire domain be populated with elements. This requirement increases significantly the number of unknowns, especially for three-dimensional problems. However, matrices that arise from this formulation have a sparse structure that simplifies their solution and reduces the computational effort.

The hybrid finite element/statistical energy analysis combines a deterministic method (finite element analysis) with a statistical method (statistical energy analysis).

The hybrid method is described in several papers [6–8]. This particular implementation of the hybrid FE/SEA method specifically involves coupling an FE structural model to a SEA acoustic model. In this case, the acoustic space is an infinite space (as opposed to an enclosed cavity). The structure "feels" the effect of the fluid and radiates sound. The SEA model of the fluid structure interaction allows for a few more approximations than the other methods. Exact approximations depend on how surfaces are meshed. Surfaces are broken up into simply connected regions, called faces. Faces are the key to the hybrid coupling and determine where assumptions are made. Assumptions made on each face are: (1) each face is assumed to be uncorrelated from adjacent faces, (2) the curvature of each face is ignored, and (3) each face is considered to have baffled boundary conditions. Making the faces as large as possible typically makes the analysis more effective, mostly due to the first assumption, but somewhat due to the third assumption. However, sometimes large surfaces of a structure are not well approximated as flat faces. Gentle curves do not present a problem, but some curvatures have an impact. Nevertheless, even with these assumptions, the hybrid method was developed for and should have good accuracy in the midfrequency region (500–2000 Hz). The hybrid method can be as much as two orders of magnitude faster than some of the other methods.

12.3.2 Microphone phased arrays and beamforming

One of the first steps in any noise control program is the identification and location of dominant noise sources. It is critical that control measures attenuate the sound radiated by these dominant sources or they will not be effective. This is especially true in large machines where there are numerous noise sources and where treating a lower-level source may have no effect on the overall noise level.

Microphone phased array (MPA) technology is an effective and very efficient tool to identify the physical location and the frequency content of dominant noise sources in mining equipment. The main advantage of MPA technology is the improved speed for the noise source identification process. In general, it takes a few minutes to collect and process the data using MPA technology, in contrast to several hours or even days of data collection required when using acoustic intensity measurements to identify dominant noise sources.

MPA technology comprises two components: (1) hardware, which consists of an array of microphones distributed in a predetermined pattern and a data acquisition system capable of sampling microphone data simultaneously up to the maximum frequency of interest; and (2) a computational algorithm known as beamforming. This algorithm adjusts the phase of the microphone signals based on a grid of assumed source locations, and a source model. The most commonly used model is that of a monopole source.

In its most simple form, the beamforming algorithm assumes that a sound source (e.g., a monopole source) exists at each grid point location. Then, for each assumed noise source, the time delay between the grid point and each of the microphones is computed. Next, the measured microphone signals are time shifted according to the computed time delays and summed up. If an actual noise source is located at the assumed source location, the shifted microphone signals will be in-phase and the summation of the signals divided by the number of microphones will represent the acoustic signal at the center of the microphone array. However, if no actual noise source exists at the assumed source location, the summation of the time-shifted signals will diminish.

Most beamforming algorithms take advantage of the computational efficiency of the fast Fourier transform (FFT) and thus process the data in the frequency domain [9]. However, for moving noise sources, time domain beamforming algorithms have been traditionally used. Nevertheless, a new technique has been developed to conduct beamforming on moving sources of sound that process the data in the frequency domain and is therefore significantly less computationally intensive than traditional time domain beamforming [10,11]. This technology has been demonstrated to be a very effective tool to identify noise sources in mid- and high-frequency ranges (above 1000 Hz). It can be used at frequencies below 1000 Hz; however, the resolution of the acoustic maps decreases significantly requiring additional postprocessing algorithms. Some of these algorithms involve deconvolution methods [12] while others take advantage of the spatial coherence characteristic of noise sources [13].

12.3.3 Source path contribution analysis

There are many cases where due to the complex machine geometry, large dimensions of a machine, and the presence of different noise sources, it is not clear through what paths noise is being transmitted from source to receiver. In general, sound can be transmitted via structure-borne and/or airborne paths. In this context, a test-based approach known as source path contribution (SPC) analysis has been shown to be very helpful.

Several SPC methods are available and they all fall into one of two categories: (1) the synthesis approach; or (2) the decomposition approach. In the synthesis approach, noise arriving at the receiver is calculated as a sum of the contributions from each source; i.e., source strength multiplied by the transfer function between that particular source and the receiver. These transfer functions are measured experimentally using a volume velocity source at the receiver and microphones at the assumed source locations. Since source strengths cannot be measured directly, they are estimated from measurements at so-called indicator locations; i.e., locations in close proximity (within 2–5 cm) to the assumed source locations. Using the volume velocity source, transfer functions between indicator locations and assumed source locations are measured. Next, this matrix of transfer functions is inverted and multiplied by the vector of acoustic responses measured at indicator locations when the machine is in operation. This product yields a vector of estimated source strengths.

In contrast, the decomposition approach separates the sound arriving at the receiver into a number of components according to some criteria based on a reference signal [14]. Once sources are identified and critical transmission paths determined, then noise controls can be developed to reduce noise levels at the receiver; i.e., the operator location.

12.4 Case studies

In this section, three case studies are presented describing the development of noise controls for underground coal mining equipment.

12.4.1 *Noise controls for longwall-cutting drums*

Longwall systems are sets of machines that work in full synchrony to extract ore from underground mines. Although there are two basic types of longwall systems—shearers and ploughs—in the United States (US), approximately 98% of longwall mines use shearers. These systems are mainly used in coal, but also a few trona mines. As shown in Fig. 12.1, a longwall system comprises the following components: a shearer that traverses back and forth along the face ripping coal; an armored face conveyor (AFC) that runs along the face and transports the ripped coal to the stageloader; powered self-advancing longwall shields that provide temporary roof support for the shearer and the AFC; and the stageloader, which, after crushing the coal, loads it onto a belt conveyor to be taken out of the mine. The shearer measures from 8 to 12m in length, and by virtue of its ranging arms can perform cuts of 2 to 6m in height. Each shield measures from 1.5 to 2m in width, and therefore on a typical 400-m-long face there are over 200 shields providing temporary roof support. Since the AFC runs along the entire length of the face, typical AFCs can measure 400m in length.

The longwall shearer is the main component of a longwall system. It is usually controlled by two operators who move along with it as it traverses the face. Its function is to rip the coal and push it into the AFC. In order to effectively accomplish these two

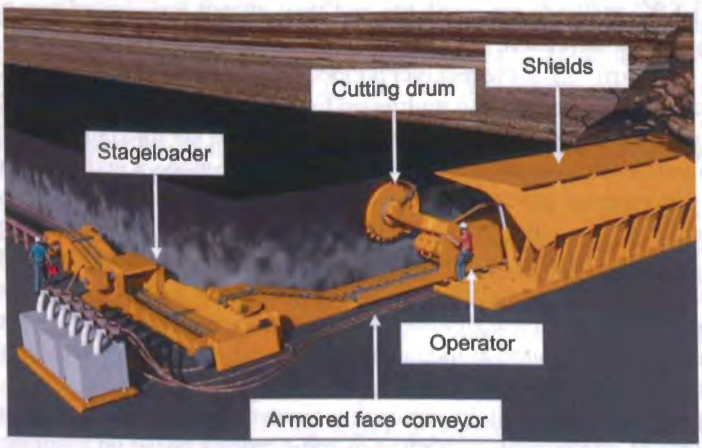

Fig. 12.1 Schematic representation of a longwall mining system showing the location of the shearer operator with respect to the cutting drum.

tasks, the shearer is provided with two rotating cutting drums—the headgate drum and the tailgate drum. These drums are named in reference to their location as being either nearest headgate or tailgate entries, but either can function as the "leading drum." When the shearer travels from headgate to tailgate, the tailgate drum is the leading drum that performs most of the coal cutting, while the headgate drum is mostly in charge of a cleaning operation by pushing coal left by the leading drum into the AFC. When the shearer travels from tailgate to headgate, the drums switch functions, with the headgate drum being the leading drum and the tailgate drum performing the cleaning job.

Noise exposure samples collected from longwall system operators by MSHA between 2002 and 2011 show that approximately 48% of these operators were exposed to noise levels exceeding the permissible exposure level, or PEL [15]. In response to this finding, NIOSH conducted research to develop engineering noise controls for longwall mining systems that would reduce the noise exposure of longwall operators.

Noise assessments conducted by the US Bureau of Mines (USBM) indicated that cutting drums are the dominant sound-radiating components on a longwall shearer [16]. These drums are set into vibration by the excitation forces that arise from the interaction of the cutting bits with the coal and transmitted to the drum through the bit holders. Due to adverse conditions at the face while the drum is in operation, i.e., as the drum is sumped into the coal, vibration measurements are extremely difficult to conduct on an operating drum. In addition, the presence of explosive gases at the face of coal mines, as well as the limited number of instruments approved for underground use in the US, further restricts the ability to perform any type of vibration and/or force measurements. Therefore, in order to reduce the sound radiated by the cutting drums, numerical models of the drums were used to explore the effect of various noise control concepts on the surface vibration and on the acoustic radiation of the drum [17]. Inputs to these models in the form of coal-cutting forces were obtained experimentally using a self-contained, intrinsically safe instrumented bit developed during the course of the project [18].

The longwall shearer-cutting drum examined in this study consists of a cylindrical body with a 0.987-m outside diameter, a 1.067-m height, and a 0.05-m-thick wall. Inside this cylindrical body, there is a circular mounting plate 0.10 m thick having a square opening at the center of the cylinder (refer to Fig. 12.2). The drum is made entirely of steel and weighs 4707 kg. Around the cylindrical body, four helical vanes are welded, starting in the face ring and winding around the cylindrical body toward the discharge side of the drum. The function of the helical vanes is to push the cut coal into the AFC as the drum rotates. The vanes have a 1.91-m outside diameter. On the outermost edge of the vanes, there are 28 bit holders that hold the cutting bits at various angles of attack. There are also 12 bit holders on the outermost edge of the face ring and 4 bit holders in the flange of the face ring, making a total of 44 bit holders. Water is carried through conduits inside the vanes to the bit holders, where the water is sprayed through nozzles to reduce the risk of ignition of mine gases and for dust control purposes.

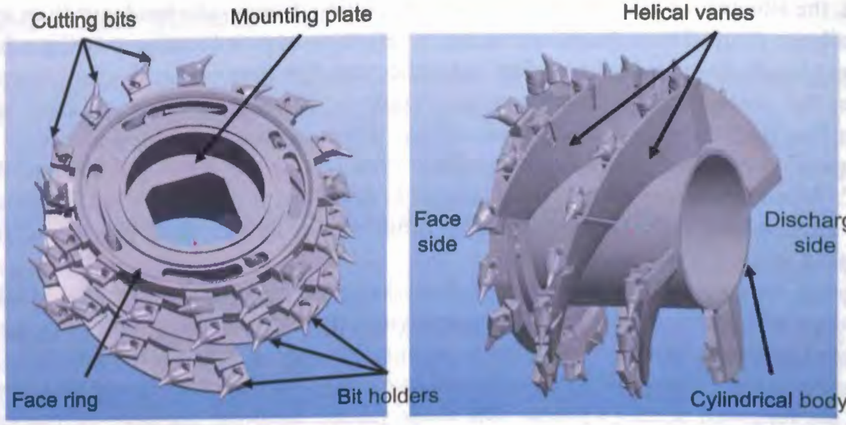

Fig. 12.2 Drawings of a longwall-cutting drum showing its various components.

12.4.1.1 Noise source identification

Although the cutting drums were found to be the dominant sound-radiating components on a longwall shearer, it was not clear what components of the drums were radiating most of the noise. To identify these components, a panel contribution analysis was performed using the boundary element model and dividing it into two parts: the cylindrical shell and the vanes. During this analysis, only one of these parts is assumed flexible while the other is set to be rigid. Analysis results indicated that the four vanes are the critical components of the drum that generate noise of much higher amplitude as compared with the noise generated by the cylindrical shell [19]. However, because of the large dimensions of the vanes, more detailed information was needed.

In order to gain a better understanding of the critical sound-radiating components on the drum, a further panel contribution analysis was performed. In this analysis, the whole drum was divided into three parts: the cylindrical shell face, inner vane segment faces, and outer vane segment faces, as shown in Fig. 12.3.

The excitation was applied in the same manner as in the prior work [20], and the predicted overall sound energy distribution is shown in Fig. 12.4. Similarly, the energy

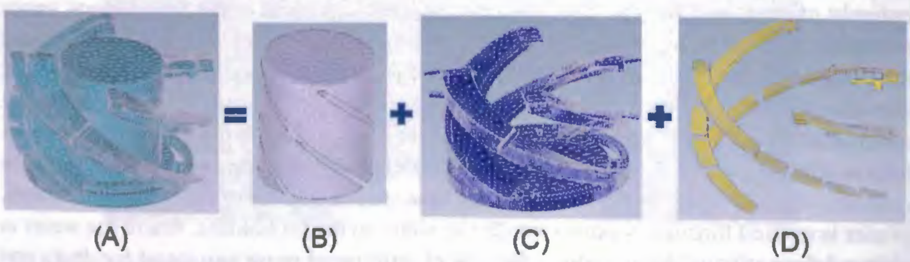

Fig. 12.3 FE-BE faces for: (A) whole drum, (B) cylindrical shell, (C) inner vane segments, and (D) outer vane segments.

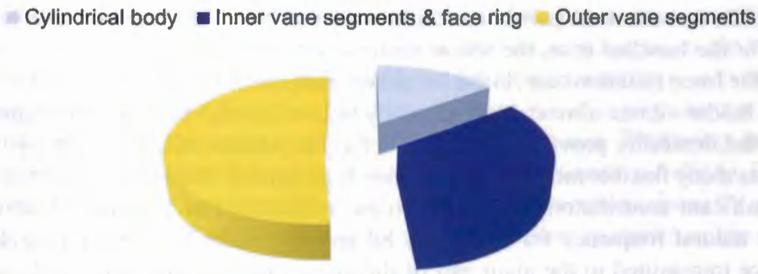

Fig. 12.4 Overall sound energy distribution computed from a panel contribution analysis.

of the noise generated by the vanes, which is the summation of the yellow and dark blue segments, dominates the total noise radiated by the drum. Furthermore, it is observed that the outer vane segments contribute more than the inner vane segments to the total noise radiation [21]. This information suggests potential noise control strategies to reduce the radiated noise.

12.4.1.2 Potential noise control concepts

Validated FE and BEM models of the cutting drum along with operational coal-cutting forces measured with the instrumented bit were used to study three different noise control concepts [21]. At this stage, only the potential of each control concept to reduce the sound radiated by the drum was assessed. This section presents a summary and a brief evaluation of the three noise control concepts that were studied as part of this research.

Force isolation

The force isolation noise control concept aims at reducing the dynamic coal-cutting force being transmitted from the cutting bits to the main drum structure. This noise control concept is schematically shown in Fig. 12.5. In order to isolate the dynamic coal-cutting force, the top layer of the connecting mass block (1-in. or 2.5-cm thickness), shown in Fig. 12.5C, was given the properties of a rubber material. The rest of the connecting mass block shown in Fig. 12.5B, the bit and bit holder system shown in

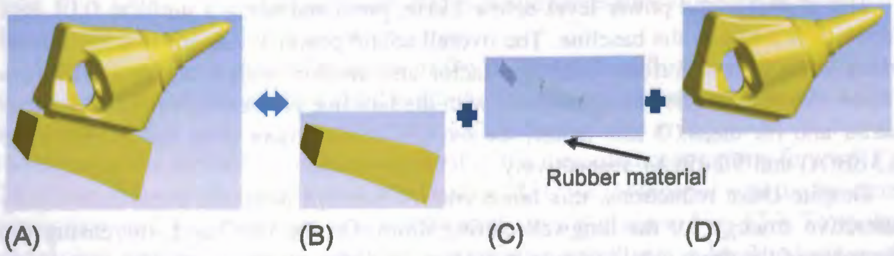

Fig. 12.5 Schematic of the bit isolation concept: (A) bit assembly, (B) connecting mass block, (C) rubber material, and (D) bit and bit holder.

Fig. 12.5D, and the main part of the drum were still given the material properties of steel. For the baseline case, the whole drum was defined as steel.

For the force isolation case, in the frequency range of interest (below 2 kHz), the bit and bit holder vibrate almost as a rigid body with relatively low natural frequencies, due to the flexibility provided by the rubber layer. Meanwhile, the main part of the drum has many flexible modes with relatively high natural frequencies, some of which are significant contributors to the total noise radiation. For frequencies above the highest natural frequency for which the bit and bit holder behave as a rigid body, the force transmitted to the main part of the drum can be significantly reduced, due to the −20 dB/decade slope of the transfer function. However, at frequencies where the bit and bit holder behave as a rigid body, larger forces can be transmitted to the main drum structure due to the resonance.

To reduce the force transmission for all the frequencies, the drum design should be modified so that the highest natural frequency of the bit and bit holder assembly rigid modes is lower than the first flexible mode of the main drum structure. In practical terms, natural frequencies of the bit and bit holder system can be adjusted by using different rubber materials.

In this study, the properties of actual industrial rubber materials were used to evaluate the effect of the bit isolation concept on sound radiation, and significant sound power reduction of up to 25.9 dB(A) was achieved. However, after the authors discussed this concept with cutting-drum design engineers, it was concluded that this concept is not suitable for the cutting drum due to adverse cutting performance and durability issues that the viscoelastic material would pose.

Damping treatment

Experimental modal analysis tests conducted on a newly manufactured drum indicated that the longwall-cutting drum is very lightly damped [17]. A uniform 0.01 loss factor was used for the structure in the structural-acoustic simulation as an approximation of the damping ratio obtained experimentally [20]. Due to the small damping ratio, there are many sharp peaks in the predicted sound power level spectra. Those peaks can be suppressed by increasing the damping ratio of the drum. Therefore, the effect of increasing the damping on the predicted overall sound power level of the noise radiated by the longwall-cutting drum was evaluated using numerical models.

The overall sound power level below 2 kHz, predicted using a uniform 0.01 loss factor, was taken as the baseline. The overall sound power levels for two additional cases—one with a uniform 0.02 loss factor and another with a uniform 0.03 loss factor—were calculated and compared with the baseline prediction. For the 0.02 loss factor and for the 0.03 loss factor, the overall sound power level reductions were 3.3 dB(A) and 5.2 dB(A), respectively.

Despite these reductions, this noise control concept does not constitute a very attractive strategy for the longwall-cutting drum. On the one hand, increasing the damping of the drum would require some type of damping treatments (e.g., attaching a layer of viscoelastic material to the surface of the drum), which, due to the adverse environment, would have durability issues. On the other hand, it would not be practical to treat the whole cutting drum. Performing damping treatments on the outer vane segments, which contribute the most to the total noise radiation, might be much easier and more practical. However, by applying damping treatments to only the outer vane segments, there is a theoretical maximum sound power level reduction, which occurs when the treated components do not radiate any noise. That being the case, the largest noise reduction that could be achieved is approximately 3 dB(A), because the noise generated by the vibration of the outer vane segments accounts for approximately 50% of the total noise radiated by the whole drum, as shown in Fig. 12.4.

Structural modification

The predicted sound power level spectrum has two dominant characteristics that relate to the vibration of the structure, and provide an excellent basis for developing structural modifications for suppressing noise radiation. The first characteristic is that the sound power level has a large amplitude when the direction of the dynamic deformation of the cutting bit either aligns with, or has a large component along, the direction of the excitation force. A straightforward solution to this condition is to minimize the amplitude of the cutting-bit dynamic deformation in the frequency range of interest. This is done by increasing the stiffness of the cutting-bit assemblies. The second characteristic is that the outer vane segment vibration contributes the most to the total noise radiated by the longwall-cutting drum. As a result, reducing the number of outer vane segment modes in the frequency range of interest also reduces the radiated sound.

Helical plates (1 × 2-in. or 2.5 × 5-cm cross section) were added to the model to connect bit holders to outer vane segments as shown in Fig. 12.6A. These plates served to stiffen both cutting-bit assemblies and outer vane segments. Stiffeners provide additional support for cutting-bit assemblies, and they also provide T-shaped supports for outer vane segments. Further, these stiffeners connect all bit holder assemblies located on the same vane, which significantly suppresses cutting-bit assembly out-of-phase modes that occur along the vane.

Modal analysis results of the modified cutting drum with stiffeners show that the number of modes in the frequency range of interest (below 2 kHz) was reduced by around 70 from the original 250 modes. For cutting-bit assemblies located on the face ring, there is no vane segment for the bit holder to be connected to. Therefore, an L-shape stiffener, highlighted in Fig. 12.6B, was added for each bit located on the face ring. This approach was taken instead of using continuous plate stiffeners as were used for cutting-bit assemblies located on vanes.

In order to assess the performance of the structural modifications, three different cases with excitations applied at different cutting bits were analyzed. The excitation locations for this analysis are highlighted with yellow circles in Fig. 12.6C–E. For all three cases, the applied excitation consisted of the measured coal-cutting forces [18]. The predicted overall sound power level below 2 kHz was compared with the baseline prediction, and the reduction achieved for each case is given in Fig. 12.7. From the simulation results, it can be seen that a promising sound power level reduction of approximately 3 dB(A) can be achieved by implementing these structural modifications on the longwall-cutting drum.

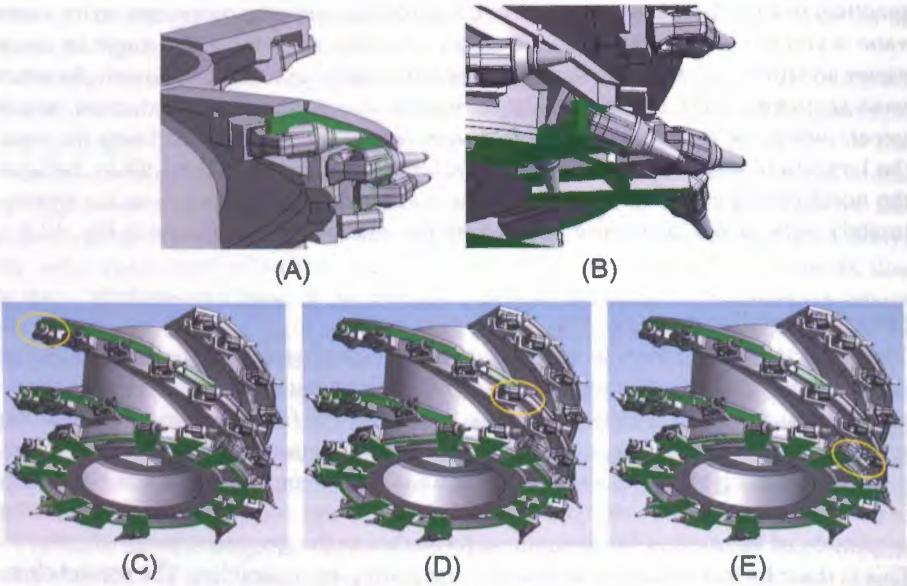

Fig. 12.6 Stiffeners and the location of excitations applied at different cutting bits to estimate the noise reduction yielded by these control concepts: (A) Plate stiffeners on helical vanes, (B) L-shape stiffeners on face ring, (C) excitation near the discharge end, (D) excitation near the center of the cylindrical body, and (E) excitation near the face side of the drum.

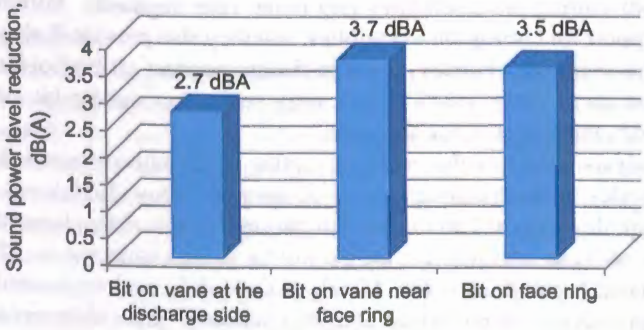

Fig. 12.7 Sound power level reduction for different excitation cases.

12.4.1.3 Constraints

Constraints that had to be observed during the development of noise controls for longwall cutting drums were as follows: First, noise controls should not affect drum-cutting performance. Second, noise controls should not affect drum-loading ability. Both of these constraints are directly related to mine production requirements. In terms of structural modifications, constraints imply restrictions on modification of helical vanes. The third constraint was that noise controls should not compromise the structural integrity of the drum. Changing a drum between scheduled overhauls is not common practice in underground longwall mines. Therefore, most longwall mines do not have spare cutting drums in stock. The fourth and final constraint is that noise controls should be durable enough to withstand rough underground mining conditions.

12.4.1.4 Selected solution

Based on these constraints and upon discussion of the potential noise control concepts with an original equipment manufacturer, it was determined that the most viable solution complying with all constraints was structural modifications to the outermost plates of the helical vanes. However, due to manufacturing and maintenance considerations, this was accomplished by replacing stiffener plates connecting bit holders to outer vane segments with gussets installed behind each bit holder, as shown in Fig. 12.8A. In addition, 1-in. (2.5-cm)-thick steel plates were welded between each gusset and the associated outer helical plate to increase the thickness of these plates, as shown in Fig. 12.8B. A total of eight ribs were used to stiffen the face plate, as seen in Fig. 12.8C.

To evaluate the performance of these controls in terms of noise reduction, a pair of standard drums were built and tested in a laboratory setup to collect baseline data. Then, noise controls were implemented into this pair of drums by making the structural modifications previously described. The modified drums with the implemented noise controls were then tested in a laboratory setup. Comparison of the data collected from the baseline drums and the modified drums confirmed the noise reduction estimated by the numerical models of the cutting drums, and thus validated these models.

The last step of the project involved evaluating the performance of these noise controls in an underground mining environment under actual operating conditions. The objective was to evaluate their effect on the longwall shearer operator's noise exposure with all other noise sources present during normal operation, especially noise

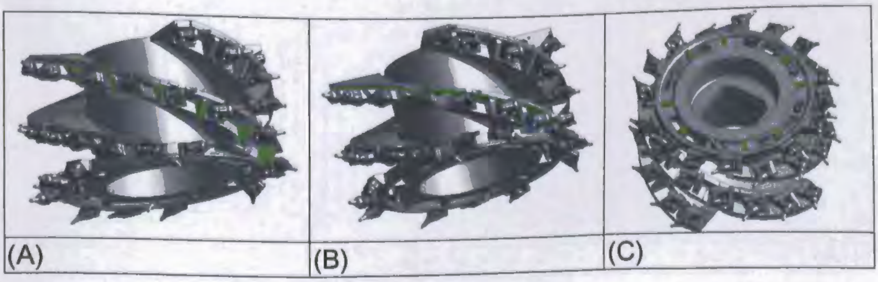

Fig. 12.8 Stiffeners and ribs *(shown in green)* implemented as cutting-drum noise controls. (A) Gussets installed behind each bit holder, (B) 1-in. thick plates between each gusset, and (C) rib stiffeners at face ring.

generated by the interaction of ripped coal with different parts of the shearer and the armored face conveyor, the water spray noise sources, and electric and hydraulic noise sources. This was the second step in validating numerical modeling results for the cutting drum under realistic operating conditions.

Sound levels were recorded using personal dosimeters at the following locations: [1] on the longwall shearer approximately 2 m away from the headgate drum, and [2] on the longwall shearer approximately 2 m away from the tailgate drum. These dosimeters were mounted on magnetic stands installed on the shearer, thus keeping them at a fixed distance from the cutting drums. Additionally, sound pressure data were recorded at the headgate drum operator location using an MSHA-permissible audio recorder at a 44.1-kHz sampling rate, while the shearer was cutting coal from tailgate to headgate. Explosive hazard restrictions prevent the use of sound level meters or more sophisticated instrumentation at the face, which limits the level of detail that can be measured. Comparison of dosimeter data collected in the mine during the use of standard cutting drums, and dosimeter data collected in the mine during the use of modified cutting drums, showed a noise reduction of approximately 2.6 dB (A) at the operator location during an 8-h period [22].

Sound pressure time data were recorded using an MSHA-permissible audio recorder. These data were then converted into the frequency domain using a fast Fourier transform (FFT) algorithm to obtain the sound pressure spectrum. Fig. 12.9 shows the unweighted and A-weighted one-third octave band spectrum of the data recorded at the collaborating mine while operating with the standard (baseline) drums as well as the spectrum of the data recorded while operating with the modified cutting drums. The spectra show a reduction throughout the frequency range. This broadband reduction is a major accomplishment that was not attainable with any other noise control options. In terms of overall sound pressure level, a reduction of approximately 3 dB is observed using the unweighted spectra; however, when these spectra are A-weighted, the overall sound pressure level reduction is approximately 6 dB.

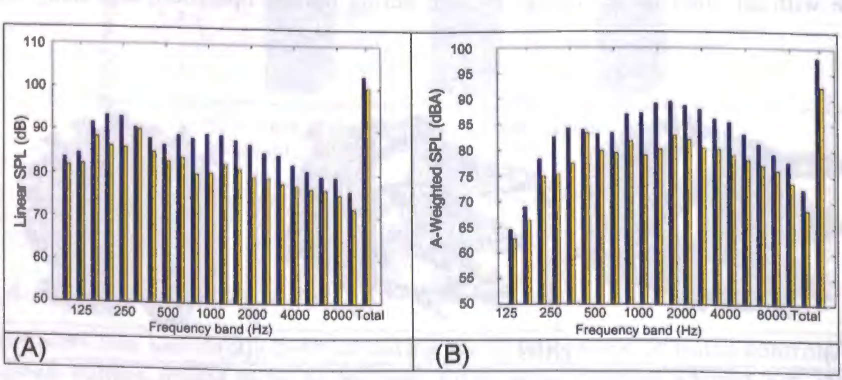

Fig. 12.9 Sound pressure spectra of the standard (baseline) drum in *gray bars* and the modified drum in *yellow bars*, computed from audio recordings at the shearer operator location during normal operation. (A) Linear spectra. (B) A-weighted spectra.

12.4.2 Noise controls for roof-bolting machines

Roof-bolting machines are extensively used in underground coal mines to drill and install bolts for roof support. The majority of these machines involve a manual cycle where the operator inserts a drill steel into the chuck and drills the hole, then inserts an epoxy cartridge into the hole, removes the drill steel from the chuck, and replaces it with a roof bolt tool to install the bolt. These many interactions between operator and machine drilling head require that controls, and thus the operator, be in close proximity to the drill steel.

12.4.2.1 Noise source identification

To identify the location and the frequency content of dominant noise sources during the roof-bolting cycle, a 1.92-m-diameter, 42-channel microphone phased array was used. Testing was conducted in NIOSH's hemi-anechoic chamber with a Fletcher Model HDDR, dual head roof bolter, as shown in Fig. 12.10A. Interior dimensions of this chamber are approximately 17.7 m long by 10.4 m wide by 7.0 m high or approximately 1300 cubic meters. This facility meets ISO 3744 requirements [23] down to approximately 100 Hz. Sound pressure level measurements were also taken at the operator location, as shown in Fig. 12.10B, to determine the overall A-weighted sound level at the operator's ear while drilling.

A large steel support stand comprising rectangular tubes was fabricated by NIOSH to hold the drilling media, shown in Fig. 12.10. To prevent the support stand from radiating significant amounts of sound, sand was used to fill the hollow tubes except for the diagonal tubes and the horizontal tubes along the short direction at the top of the structure. This was done for convenience and to create a vibration impedance mismatch in the structure to reduce vibration transmission.

During the formulation of the test plan, it was decided to use drill bits and drill steels that were representative of industry usage. Therefore, round and hexagonal drill steels were used along with a 34.9-mm drill bit. Granite was chosen as the drilling

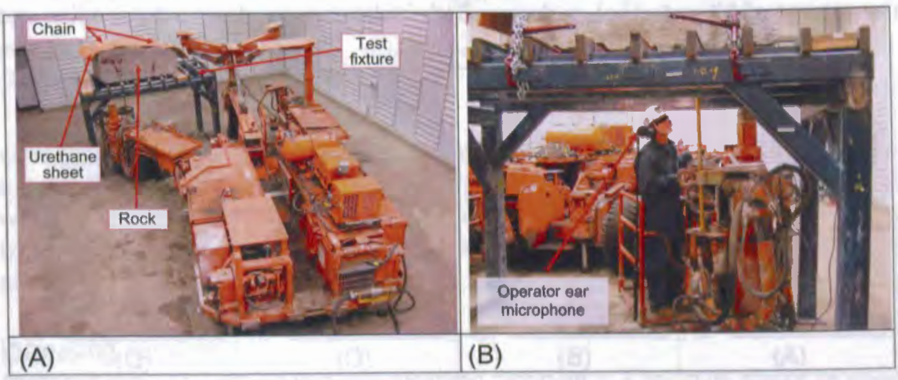

Fig. 12.10 Experimental setup used for drilling tests: (A) roof bolter in the hemi-anechoic chamber, and (B) location of the operator ear microphone.

media because of its high compressive strength. Past research at NIOSH showed that drilling into higher-compressive strength materials generates more noise than drilling into lower-compressive strength materials [24]. Therefore, granite would provide the worst-case scenario for noise emission. Also, a low rotation speed of 200 rpm and a low thrust of 2121 lbs. were used during testing. Previous NIOSH research showed that when drilling into hard materials, lower rotation speeds should be used [25]. The lower thrust was used, so a longer drill time could be obtained.

Fig. 12.11 shows acoustic maps obtained from beamforming measurements for 2500–6300 Hz one-third octave bands. 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. 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 [26].

Fig. 12.12 shows the one-third octave band spectrum at the position of the roof-bolting machine operator's ear. The overall sound level at the operator's position was 99.7 dB(A). The frequency content of the noise radiated toward the operator is dominated by the 1250–8000-Hz frequency bands.

12.4.2.2 Potential noise control concepts

To reduce the sound level at the operator ear location while drilling, noise controls must target the noise generated at the drill bit and rock interface as well as the drill steel and drill chuck interface. In addition, the controls must address the mid- to high-frequency components of the drilling noise. To reduce the radiated sound at both bit and chuck interface, isolation techniques were used.

Force isolation

A bit isolator was developed to reduce the noise radiated at the bit and rock interface [27]. A chuck isolator was also developed to reduce the noise radiated at the drill steel bit and drill chuck interface [28]. Fig. 12.13 shows the first prototypes built to prove the concept of bit and chuck isolators. Both isolators were designed for noise and

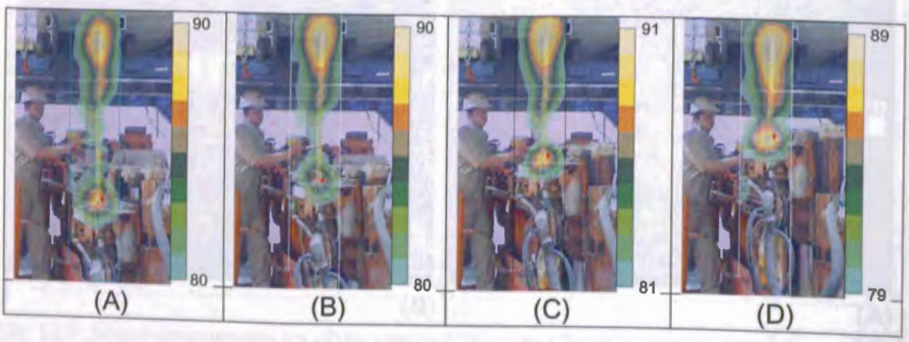

Fig. 12.11 Beamforming results for a 1.2-m hex drill steel at drilling depths of: (A) 0 m (start of hole), (B) 0.15 m, (C) 0.30 m, and (D) 0.45 m.

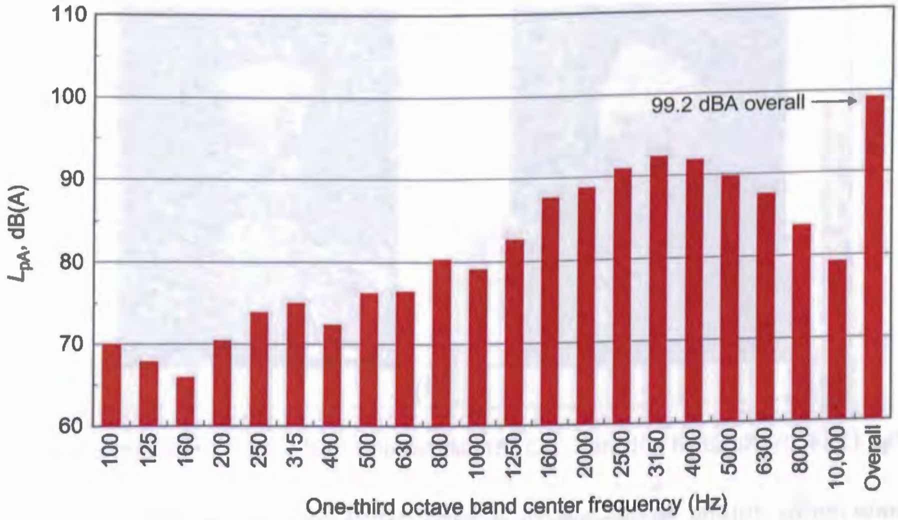

Fig. 12.12 Baseline operator ear sound pressure level with a 1 $^{3}/_{8}$-in. (3.5-cm) drill bit.

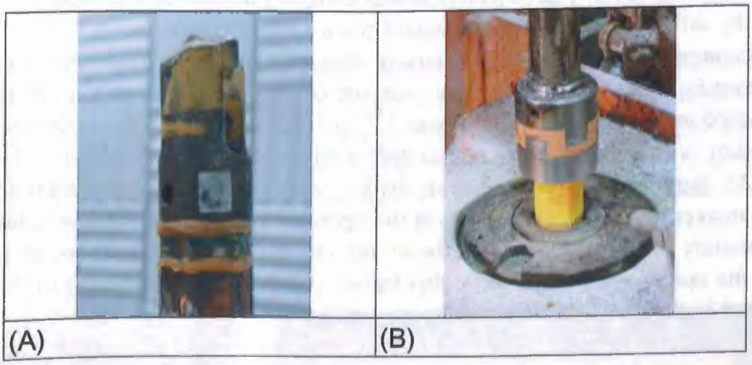

Fig. 12.13 Vibration isolation noise control concepts built to assess potential noise reductions: (A) bit isolator, and (B) chuck isolator.

vibration damping to reduce the noise emitted during drilling by limiting the vibration transmitted down the drill steel from the drill bit/media interface. A urethane material with a durometer of 58 Shore D was chosen for both isolators to reduce the dominant frequency bands between 1250 Hz and 8000 Hz. The chuck isolator used a jaw-type urethane coupler.

Increasing damping

Previous research showed that drill steel/rod vibration is a common source of noise during drilling operations [29,30]. Furthermore, acceleration in a roof-bolting machine drill steel may exceed 500 g, suggesting that this is the cause of significant

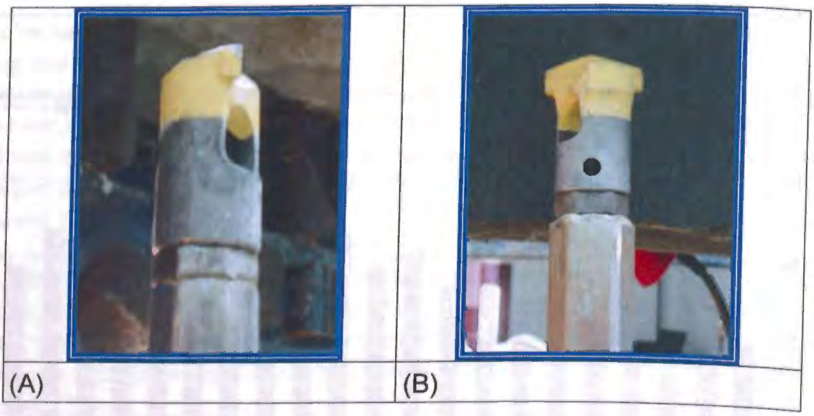

Fig. 12.14 (A) Standard drill steel, and (B) damped drill steel using a constraining layer.

noise during drilling. In this context, a damped drill steel noise control concept was built and tested. To this end, constrained layer damping was used to create a damped drill steel. Fig. 12.14. shows a standard drill steel and a damped drill steel with an outer constraining steel layer. The objective of this damping treatment is to reduce vibration induced by drilling, which, in turn, would reduce noise radiation.

To accommodate for the larger outside diameter resulting from the constrained layer damping treatment on the outer surface of the drill steel, a $1^5/_8$-in. (4.1-cm) bit was used instead of the conventional $1^3/_8$-in. (3.5-cm) bit. At the operator's location, drilling with a standard hexagonal drill steel yielded sound levels on the order of 101 dB(A). Similar data collected while drilling with the damped hexagonal drill steel yielded an average value of 97 dB(A) at the operator position, showing a reduction of approximately 4 dB(A). Fig. 12.15 shows the one-third octave band sound pressure level at the operator location. From this figure, it can be seen that most of the sound is radiated in the 1600–6300-Hz frequency range.

Acoustic enclosure/sound barrier

A third type of noise control concept was investigated using the acoustic enclosure/sound barrier approach. A prototype of a collapsible drill steel enclosure (CDSE) noise control was built to block part of the noise being radiated by the drill steel from reaching the operator. The first CDSE prototype, shown in Fig. 12.16, consists of a round aluminum-coated fiberglass bellows with a spring enclosed inside the bellows. This prototype was mounted on the drill head, near the chuck, and enclosed the drill steel. The purpose of the spring was to keep the bellows raised up when installed vertically on the roof bolter. As the drill head raises to the mine roof, the spring compresses downward, allowing the CDSE to encapsulate the drill steel throughout the drilling process. Fiberglass was chosen because it has good acoustical absorptive properties, has excellent heat resistance, and is incombustible. The fiberglass bellow dimensions were 1.905 cm thick by 19.685 cm outside diameter and an extended length of 1.2192 m.

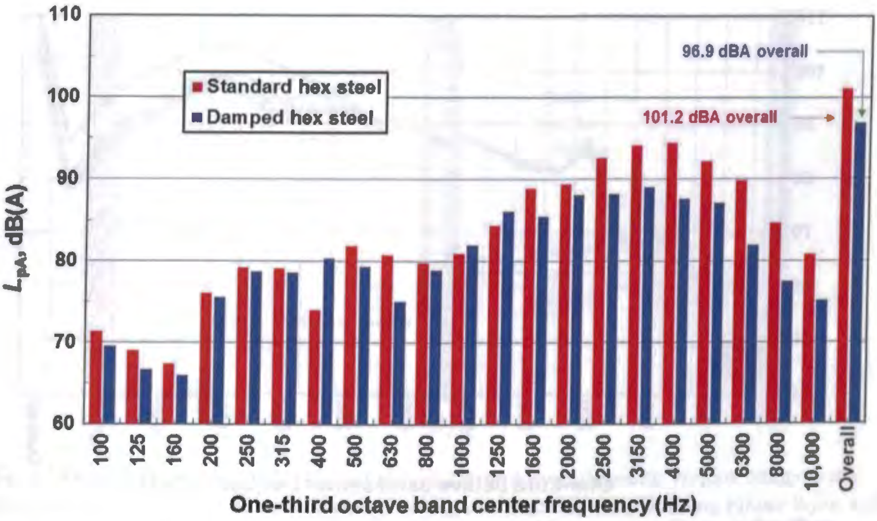

Fig. 12.15 Sound pressure level radiated by standard and damped drill steels with $1^5/_8$-in. (4.1-cm) drill bits.

Sound power levels radiated by a standard drill steel when drilling into granite were compared to the sound power radiated using the CDSE under the same conditions. In addition, tests were conducted with varying gaps between the top of the CDSE and the bottom of the drill media. Varying gaps would determine how tight of a seal was needed between the CDSE and the rock media in reducing sound power levels. Gap lengths of 15.24 cm, 10.16 cm, 7.62 cm, 5.08 cm, and no gap were tested.

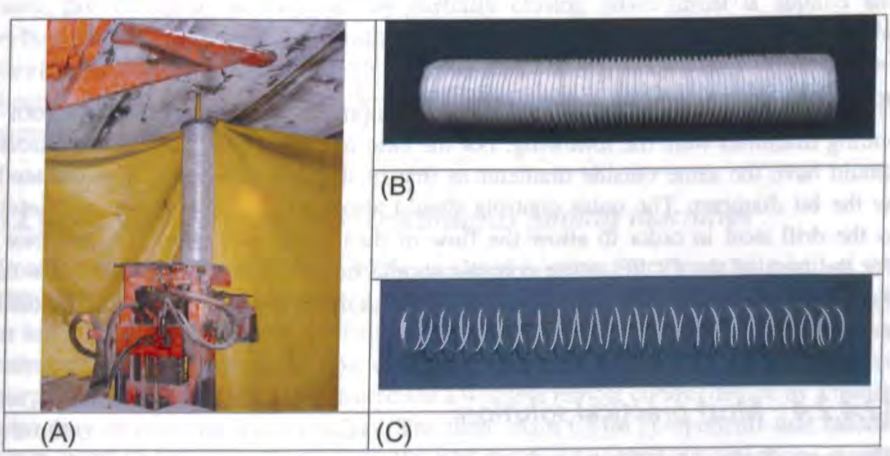

Fig. 12.16 Prototype of the collapsible drill steel enclosure (CDSE) noise control concept: (A) installed on a roof bolter machine, (B) outer layer, and (C) inner spring.

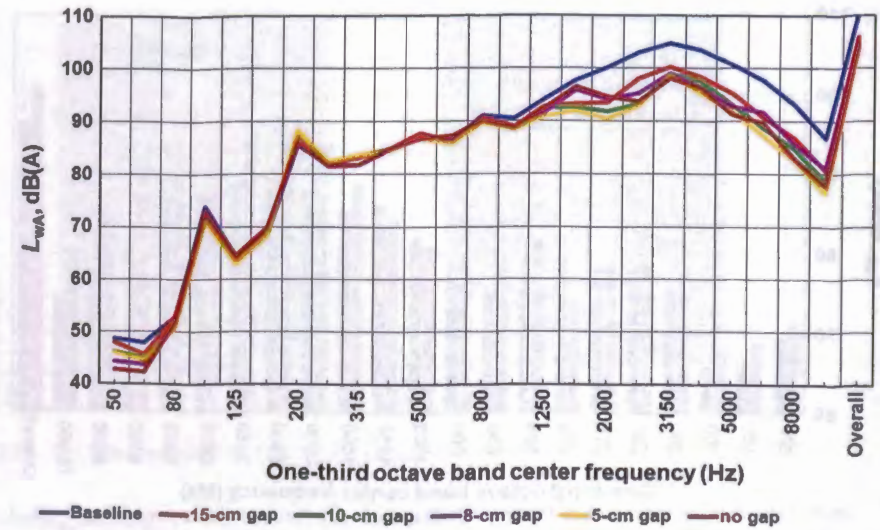

Fig. 12.17 One-third octave band spectrum for all configurations while drilling in granite at 200 rpm and 9.4 k-N thrust.

Fig. 12.17 shows the one-third octave band spectrum for drilling in granite at 200-rpm speed and 9.4 kN thrust for all configurations. From this figure, it can be seen that the CDSE resulted in a sound power level reduction of 6 dB(A) with gaps of 10.16 cm, 7.62 cm, 5.08 cm, and no gap. However, with a 15.24-cm gap, the sound power level was only reduced by 5 dB(A). More generally, Fig. 12.17 shows the effectiveness of the CDSE in reducing the radiated sound power in the frequency range of interest (1250 Hz–8000 Hz).

12.4.2.3 Constraints

The constraints to be observed during the development of noise controls for roof-bolting machines were the following: For the case of the bit isolator, noise controls should have the same outside diameter as that of the drill steel, which is dictated by the bit diameter. The noise controls should also have the same inner diameter as the drill steel in order to allow the flow of dust particles to the dust collector. For the case of the CDSE, noise controls should not block the operator's view of the drill steel. Finally, noise controls should not risk the structural integrity of the drill steel-bit assembly.

12.4.2.4 Most practical solution

The most practical solution complying with all constraints was the drill bit isolator (DBI). After various refining iterations, the final DBI consists of two hollow steel cylinders with a rubber layer between them. A schematic of the device is shown in

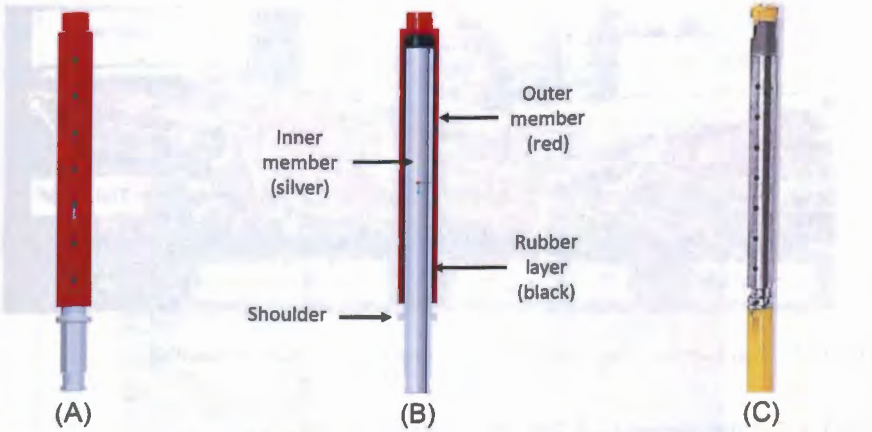

Fig. 12.18 Details of the DBI: (A) diagram of the prototype detailing various components, (B) close-up of inner and outer members showing the location of the isolating rubber layer, and (C) an actual DBI equipped with a 35-mm drill bit and installed on a hexagonal drill steel.

Fig. 12.18. The rubber layer between the inner and outer cylinders isolates vibrations at the drill bit from the drill steel, thereby reducing the noise radiated from the drill steel. This layer is chemically bonded to the steel components to limit torsional travel and produce consistent stiffness. Fig. 12.18B is a close-up view of the inner and outer members and the rubber layer that separates them. The DBI has a drill steel coupling on one end and a bit coupling on the other. These couplings are welded to the ends of the inner and outer cylinders. There is a 0.4-in. (10-mm) gap at the end of the outer cylinder, which is designed to allow for a small amount of relative movement between the layers as axial thrust loads are applied and removed. The gap acts as a safety feature, preventing axial overload by partially closing when thrust is applied and rebounding to the original position when thrust is removed. Fig. 12.18C shows the device installed on a drill steel with a drill bit attached to the end. Minor modifications based on field study results detailed here were incorporated into the final production version of the device.

12.4.3 Noise controls for continuous mining machines

Continuous mining machines (CMMs) are used to extract approximately half of the US underground coal production in room-and-pillar operations, and to develop entries in longwall mines. Unlike longwall operations where the roof collapses after coal is extracted, in room-and-pillar operations coal pillars are left behind for roof support purposes. CMMs are usually operated via a wireless remote control device by a miner who may or may not have a helper. The three main CMM components that radiate noise are the cutting head, the conveyor, and the dust scrubber fan, which are shown in Fig. 12.19. Of these three components, it was determined that conveyor noise is the most important contributor to the total radiated sound [31].

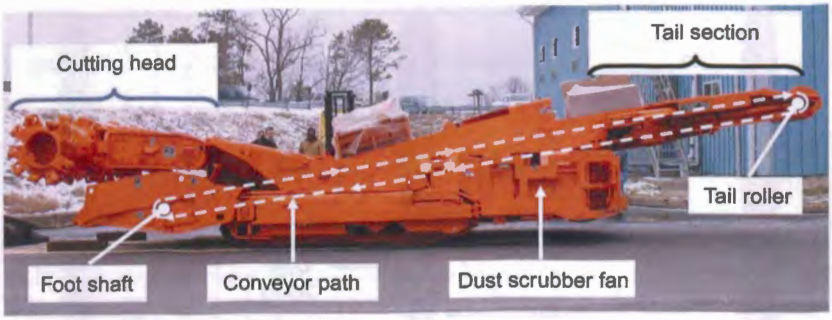

Fig. 12.19 Noise-generating components on a continuous mining machine.

12.4.3.1 Noise source identification

To identify dominant noise sources on a continuous mining machine, acoustic measurements were conducted in a hemi-anechoic chamber at NIOSH. Noise-sensing equipment included a 1.92-m-diameter, 42-element microphone phased array. The CMM under test was a new JOY Model 14CM-15 continuous miner equipped with a 956-mm-wide, 54-flight conveyor chain. NIOSH conducted beamforming testing at the cutting drum and conveyor tail ends of the CMM. The length of the CMM was several times the diameter of the microphone array necessitating a series of data measurements along both sides of the CMM and then above the CMM to evaluate the entire machine. Fig. 12.20 shows the CMM in the hemi-anechoic chamber with the microphone phased array installed above the tail section.

Fig. 12.20 CMM in the NIOSH hemi-anechoic chamber with overhead microphone array.

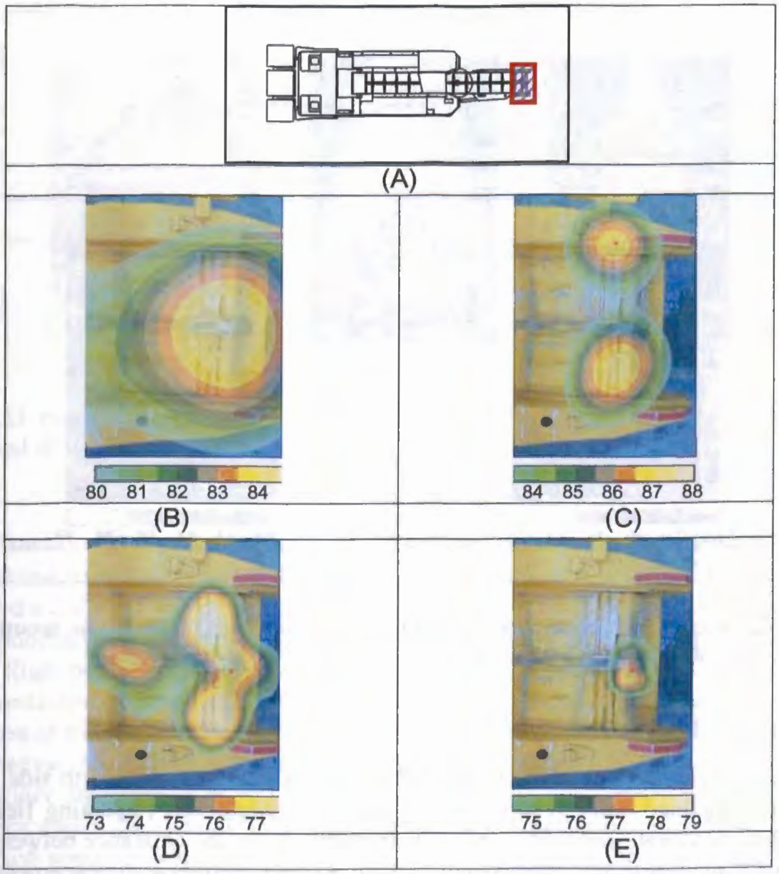

Fig. 12.21 Dominant noise sources at the tail section area (*red box* in (A)) covered by acoustic maps at: (B) 500 Hz, (C) 1000 Hz, (D) 1600 Hz, and (E) 2500 Hz.

Overhead measurements revealed dominant noise sources located at the tail section of the CMM—more specifically in the vicinity of the tail roller. Examination of the acoustic maps suggests three different noise mechanisms: [1] chain-tail roller interaction [2], flight tip-flexplate interaction, and [3] flight-upper deck interaction. Fig. 12.21 shows these sources at four different frequencies. These noise sources were previously suspected but not confirmed. It can be seen that not only do chain links impacting the tail roller (TR) generate noise at the tail section, but that impacts from flight tips on side boards and impacts from chain flights on the upper deck are also significant noise radiators. Given this scenario, an effective noise control should attenuate noise generated in these locations.

Secondary sources were identified at the front end of the left flexplate guide at 1600 Hz and 2000 Hz as shown in Fig. 12.22. Flexplates provide confinement for

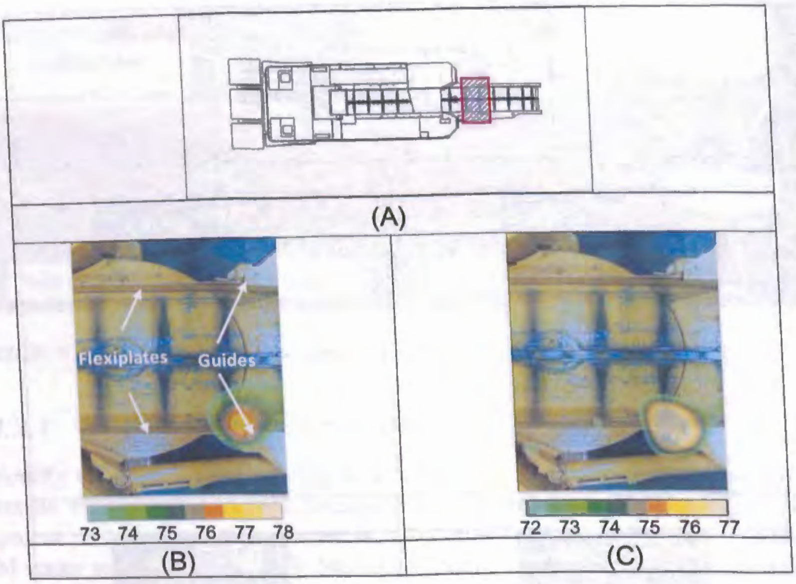

Fig. 12.22 Secondary sources at the flexplate area (*red box* in (A)) covered by acoustic maps at: (B) 1600 Hz and (C) 2000 Hz.

the coal being conveyed as the CMM tail section is swung from side to side during loading of haulage units. It is suspected that chain flight tips impacting flexplates cause them to vibrate and rattle against their guides. Since the clearance between flexplate and flight tips is only approximately 1 cm, a small transverse displacement of the chain causes impacting to shift from side to side. A similar phenomenon was observed in previous studies when the vibration of the left flexplate was greater than that of the right flexplate [32].

Other noise sources were found at the front of the machine; however, since these sources were located farther away from the operator location, they were deemed to be of lesser priority in terms of operator and helper noise exposure reduction [33].

12.4.3.2 Potential noise controls

Conveyor noise has been the subject of previous research [32,34]. From these studies, three noise controls were proposed: [1] a urethane-coated tail roller [2], a jacketed tail roller (i.e., a resilient material between an inner and an outer steel shell), and [3] urethane-coated chain flights. Fig. 12.23 shows prototypes of these noise controls.

Impact forces exerted on the tail shaft by the conveyor chain are transmitted as vibrations through the rest of the structure. Resilient materials have been placed between the chain and roller in an attempt to reduce these forces. Studies conducted

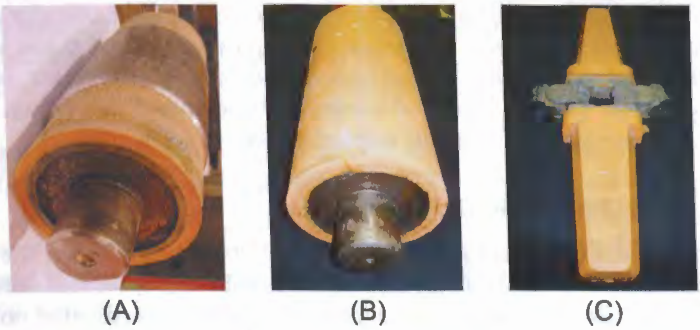

Fig. 12.23 Noise controls for tail section noise: (A) jacketed tail roller, (B) urethane-coated tail roller, and (C) urethane-coated chain flights.

by the Bureau of Mines investigated an isolated tail roller design where an elastomer was bonded to the tail shaft and protected with a steel tube [35,36]. This treatment achieved a 2-dB(A) reduction in sound level at the operator's position, but was never tested underground. Recently, a urethane coating, similar to the coating used for the coated flight bar design, was applied to the outer diameter of the tail roller [37]. In the aforementioned hemi-anechoic chamber, testing with this design resulted in a 2-dB reduction in the operator location sound level. This design failed in underground testing, however, due to high point contact loading from material (e.g., coal or overburden rock) under the chain.

To document the overall noise emission of the CMM during conveying, NIOSH conducted sound power testing in a large reverberation chamber [38]. This testing was conducted using the comparison method of sound power calculation per the requirements of the acoustic standard ISO3743-2 [39]. The same resilient material used for the urethane tail roller tested underground was used to build a prototype for testing in the reverberation chamber. During normal operation of the conveyor (i.e., conveying coal from the cutting end of the CMM to the tail section), the coal has a damping effect on the noise radiated by the conveyor. From these tests, it was determined that overall sound power level of the CMM is 116 dB(A) with a standard tail roller, and is 115 dB(A) with the urethane-jacketed tail roller. Thus, the urethane-jacketed tail roller resulted in a 1-dB reduction.

NIOSH also conducted similar ISO 3743-2 based sound power testing in its reverberation chamber to determine the effect of coating conveyor flight bars with urethane. Here, testing was conducted without loading the conveyor, both for standard tail roller tests and for urethane-coated tail roller tests. The overall sound power level of the CMM with standard chain was 117 dB(A) while the overall sound power level with the urethane-coated flight bars was 112 dB(A). This 5-dB reduction in the sound power emission was considered significant and indicated that the urethane-coated flights bars might be an effective noise control.

12.4.3.3 Constraints

The most important requirement regarding noise controls in this particular application was durability, especially since viscoelastic materials such as urethane were being used. Another constraint, common to all underground mining equipment, is that noise controls should not risk the structural integrity of the component being addressed, which was the conveyor chain in this particular case.

12.4.3.4 Selected noise control

After laboratory and field testing of multiple noise control prototypes, the conveyor chain with urethane-coated flight bars was selected as the most practical noise control. Underground tests showed that this noise control provides an estimated noise reduction of 3 dB in an 8-h time-weighted average using MSHA criteria [34]. Coated flight bars proved to be significantly more durable than the treated tail roller, with in-mine testing suggesting that the life of a coated chain equals or exceeds the expected life of a typical metal-flight chain. This noise control is commercially available and has been implemented in various mines to reduce the noise exposure of CMM operators.

Although the urethane-coated conveyor chain provides significant noise reduction, the overall sound radiated by the CMM must still be further reduced. It is likely that a CMM operator exposed to typical noise levels for an 8-h shift would still be exposed to a time-weighted average sound level exceeding the MSHA PEL. To further reduce the sound level at the operator location, and thus the noise exposure, sound radiated by the dust scrubber system of the machine needs to be addressed. Preliminary work in this area has identified various flow obstructions along the ducting and demister components that result in an off-axis nonuniform flow upstream of the fan. These obstructions create air turbulence thereby decreasing fan efficiencies and increasing noise emissions.

12.5 Conclusions

This chapter has presented an overview of research conducted by NIOSH aimed at reducing occupational noise-induced hearing loss among different mining machine operators. The approach used to achieve this goal was that of reducing sound radiated by various pieces of mining equipment such as longwall mining systems, continuous mining machines, and roof-bolting machines. For each machine, the process involved identifying dominant noise sources and developing engineered noise controls that would attenuate the sound radiated by these sources. Through this process, noise controls were developed and implemented, and in most cases retrofitted, onto machines in operation.

Interestingly, after initial dominant noise sources were attenuated by engineered controls, other noise sources became dominant. For example, drill steel vibration was identified as the dominant noise source for roof-bolting machines. Two noise controls were developed: (1) the drill bit isolator to attenuate vibrations transmitted from bit to drill steel, and (2) the collapsible drill steel enclosure, which acts as a barrier between the drill steel and the operator. However, despite significant noise reductions achieved by these controls (up to 6 dB in sound power level reduction), many roof-bolting machine operators are still overexposed from other sources that have now become dominant. This example suggests the need for continued noise source identification and ranking, followed by development of additional noise attenuation controls.

To eliminate the risk of long-term hearing loss, overall noise exposure for mine equipment operators should be 85 dB(A) (NIOSH recommended exposure limit (REL) for an 8-h shift) or less when possible. Achieving this may require attacking multiple noise sources simultaneously, resulting in a more comprehensive noise control methodology. In this context, the approach for future projects will focus on developing noise controls solutions at the design stage, i.e., quiet-by-design, rather than localized solutions for existing machines.

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