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Noise control concepts for a longwall cutting drum

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ABSTRACT

Operators of longwall mining systems are exposed to sound levels of 93-105 dB(A) and receive noise exposures that place them at risk of noise-induced hearing loss. In previous field surveys, the sound radiated by the cutting drums was identified as a major hazard, especially considering the close proximity of the drums to the operators. In this context, the National Institute for Occupational Safety and Health (NIOSH) has used finite element (FE) and boundary element methods (BEM) to model and analyze the noise radiated by a cutting drum. Based on the analysis results, three conceptual noise controls for the cutting drum were developed and evaluated numerically. The simulation results indicate that promising noise reductions (3 dB(A) or more) can be achieved by all three developed noise control concepts, damping treatment, bit isolation, and structural modification. Due to the severe operating environment in longwall mines, structural modification is believed to be the most suitable noise control strategy.

1. INTRODUCTION

Longwall mining systems produce around 50% of the coal from underground mines in the U.S, and they generate sound levels from 93 to 105 dB(A) [1-2]. This level of noise places operators of longwall mining systems at great risk for noise-induced hearing loss. In fact, an analysis of more than one million worker audiograms shows mining to have the highest prevalence of hearing loss of all the major industries [3]. To help protect miners, the Hearing Loss Prevention Branch (HLPB) of the Office of Mine Safety and Health Research (OMSHR) has been developing noise controls for longwall mining systems.

Figure 1 shows a simple representation of a typical longwall mining system, made up of a shearer, an armored face conveyor (AFC), a stageloader, and longwall shields. The shearer is equipped with two cutting drums, which rotate and move back and forth along the coal face to rip the coal and push it to the AFC. The AFC conveys the ripped coal to the stageloader. The stageloader crushes the coal and loads it onto a belt conveyor which carries the crushed coal to the surface. Throughout this process, the powered self-advancing longwall shields move forward to provide continuous temporary roof support for both the shearer and the AFC as they advance.

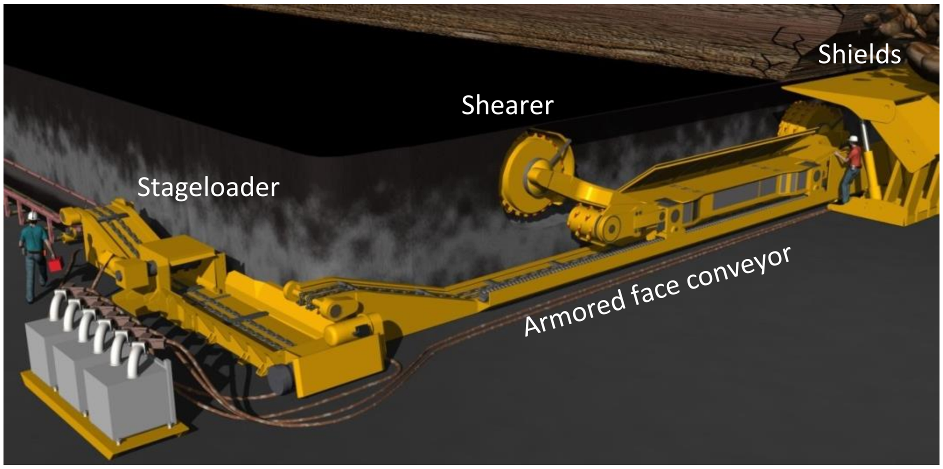


Figure 1: Schematic of a longwall system.

Previous studies indicate that the shearer [1-2] and stageloader [4-5] are the two major noise sources of longwall mining systems; in this paper, only the longwall shearer drum was considered. The longwall shearer cutting drum examined in this study consists of a cylindrical shell, around which four helical vanes are welded as shown in Fig. 2. There are 44 pairs of bit holders and cutting bits welded around the cutting drum, with 7 on the outermost edge of each vane, 12 on the outermost edge of the face ring, and 4 on the flange of the face ring. A noise radiation model of a cutting drum was developed [6] using the combined finite element (FE) and boundary element method (BEM), based on a validated drum FE model [7]. The sound radiation model was also validated by correlating the predicted and measured sound pressure levels at multiple points [6]. From this modeling and validation process, the dynamic deformation of the cutting bits and the four vanes were shown to contribute the most to the total noise radiation of the drum [8].

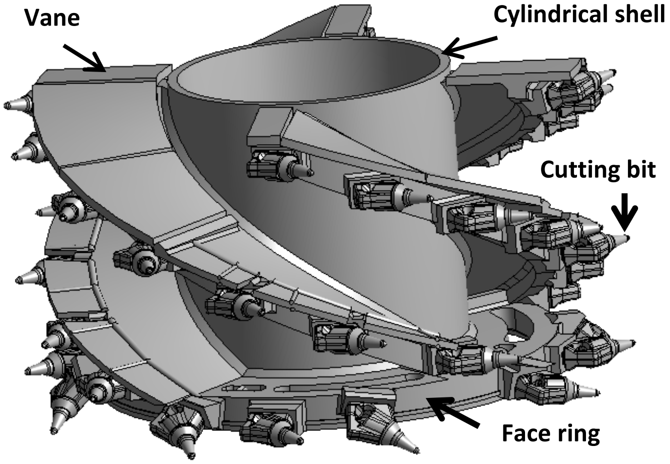
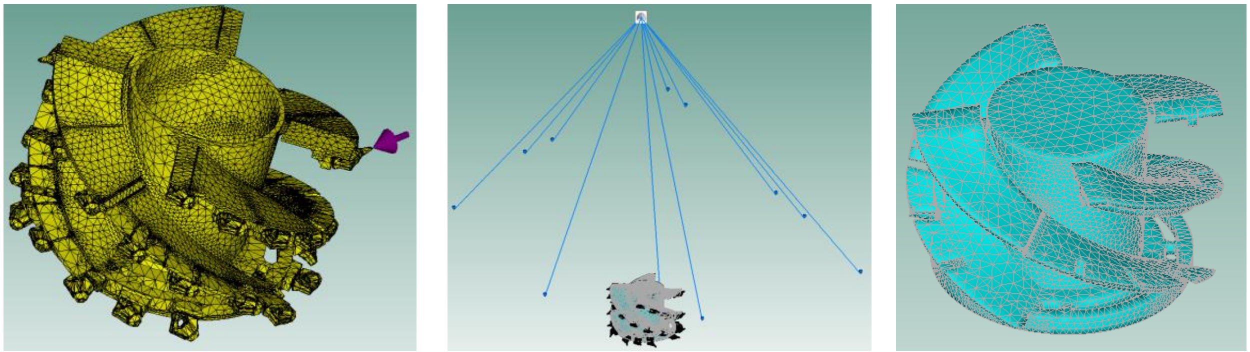


Figure 2: Structure of the longwall cutting drum.

In this paper, further panel contribution analyses were performed, and the results indicated that the outer vane segments contribute the most to the total noise radiation. Based on these findings, conceptual noise controls for the cutting drum—specifically damping treatment, bit isolation, and structural modification—were developed and evaluated numerically.

2. VIBRO-ACOUSTIC MODELING AND ANALYSES

The FE-BEM sound radiation model that was used in references [6, 8] was adopted in this study. The main body of cutting drum was modeled using ANSYS as a single solid body, with the welds represented by overlapping triangular bodies with coincident nodes at the interfaces. The structural FE model contains 584,000 elements as shown in Fig. 3(a), where the arrow represents the excitation. A constant 0.5% damping ratio was used for the cutting drum structure throughout the frequency range of interest (62.5-2000 Hz).



(a) *(b)* *(c)*

Figure 3: *(a)* structure FE model, *(b)* combined FE-BEM structural-acoustic model, and *(c)* FE-BE surface.

Within the FE-BEM structural-acoustic model, the layout of the acoustic sensors was determined based on the international standard ISO 3744, as shown in Fig. 3(b). In addition, the sound power level was calculated by the method described in the standard. A rigid, infinite surface underneath the cutting drum was defined in the numerical model in order to create a hemispherical measurement surface consisting of a free field over a reflecting plane as used in the standard. The interaction between the FE structure and the BEM fluid was represented by the FE-BEM surface, as shown in Fig. 3(c). This mesh has 10,600 elements and should be adequately meshed for analysis to 2000 Hz. The frequency range taken into account was from 62.5 to 2000 Hz (contributions above 2000 Hz is small), where 1/144th-octave-band analysis was chosen based on the damping of the cutting drum. Please refer to the previous studies [6, 8] for more detailed information.

A previous analysis of the sound radiated by the cutting drum [8] showed that the sound power level is quite sensitive to the direction of the excitation forces, and the causes of this sensitivity are explained in this study. In Fig. 4, the curves on the left are the sound power levels of the noise radiated by the cutting drum due to the excitations applied along the bending, tangential and axial directions. The pictures and the blue arrows on the right-hand side of the Fig. 4 represent the dynamic motions (modal shapes) of the cutting bit assembly. It can be easily observed from Fig. 4 that, for frequencies between 500 Hz and 1000 Hz, the sound power level due to the bending force excitation has the greatest magnitude. A detailed look at the mode shapes of several modes of the cutting drum, whose natural frequencies follow in this frequency range, showed that the cutting bit assembly vibrates approximately along the bending force direction, as illustrated in Fig. 4. Similarly, the tangential force excitation case has the highest sound power level, for frequencies between 1000 and 1427 Hz, where the cutting bit assembly vibrates approximately along the tangential force direction. For frequencies from 1427 to 2000 Hz, the sound power levels due to the axial force are much lower than the levels due to the bending and tangential forces. This is because the cutting bit assembly vibrates in a torsional mode in this frequency range, and the torsional vibration has a smaller component along the bit axial direction as compared with the components along the bending and tangential directions.

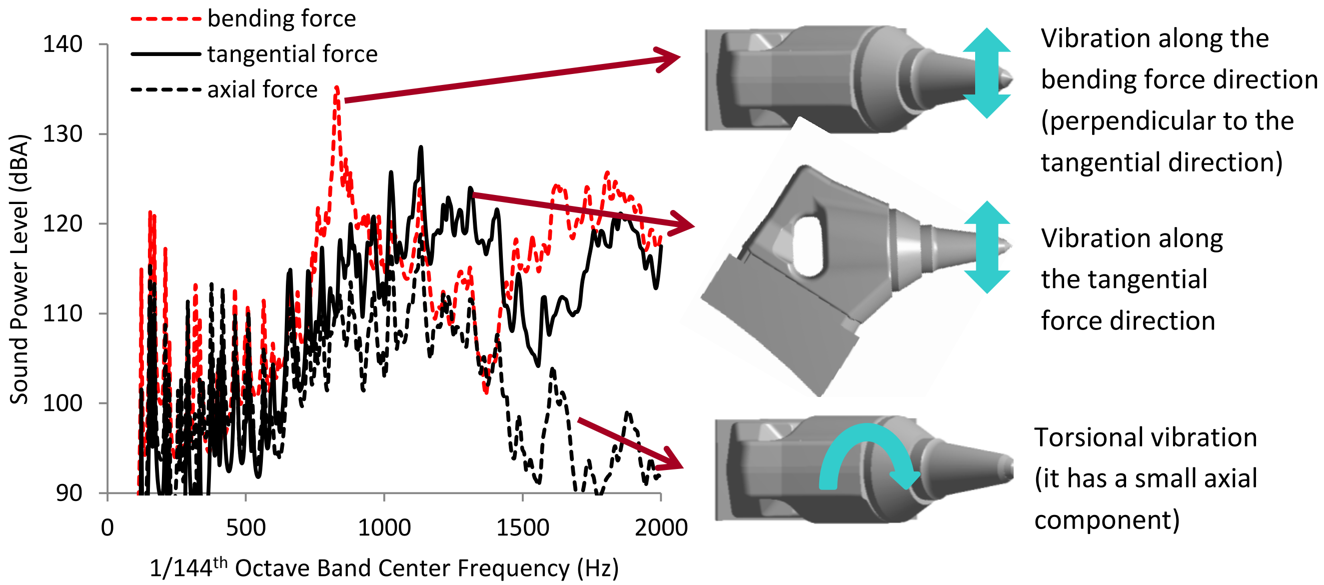
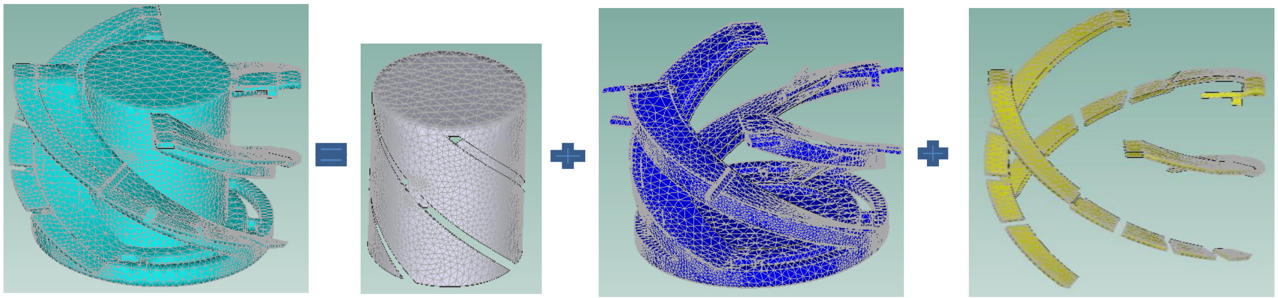


Figure 4: Sensitivity of the sound power level to the force direction (blue arrow indicates direction of motion).

From the above observations, it is clear that the sound power level will have a larger amplitude when the direction of the cutting bit dynamic deformation either aligns with or has a large component along the direction of the excitation force. This finding is reasonable because the modes, where the cutting bit has a large dynamic deformation along the direction of the excitation, can be easily excited by the force applied at that particular cutting bit, and thus generate a relatively high level of noise. This finding provides a very useful insight into the sound radiation characteristics of the drum, which aids with the development of noise controls, as will be shown in the following sections.

In a previous study [8], panel contribution analysis was performed to determine which part of the drum contributes the most to the total noise radiation, with the whole drum FE-BE surface being divided into two parts including the cylindrical shell face and the vane face. The analysis results indicate that the four vanes are the critical part of the drum, which generate noise of much higher amplitude as compared with the noise generated by the cylindrical shell. However, because of the large dimensions of the vanes, more detailed information is needed.

In order to gain a better understanding of the critical part of the drum, a further panel contribution analysis was performed in this study, where the whole drum was divided into three parts: the cylindrical shell face, the inner vane segment faces, and the outer vane segment faces, as shown in Fig. 5. The excitation was applied in the same manner as in prior work [8], and the predicted overall sound energy distribution is shown in Fig. 6. Similarly, the energy of the noise generated by the vanes, which is the summation of the yellow and 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. This information suggests noise control strategies to reduce the radiated noise.



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

Figure 5: FE-BE faces for: *(a)* whole drum, *(b)* cylindrical shell, *(c)* inner vane segments, and *(d)* outer vane segments.

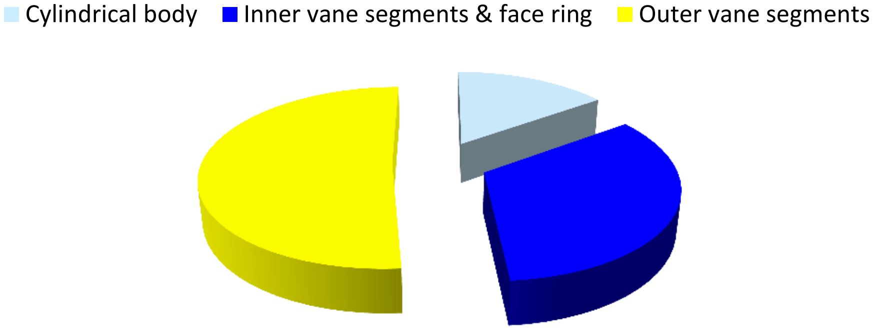


Figure 6: Overall sound energy distribution

3. CONCEPTUAL NOISE CONTROLS

A. Bit isolation

The longwall cutting drum rotates as it moves back and forth along the coal face, and as it rotates, the cutting bits hit the coal and cut the coal off. This “hit and cut” process results in very large dynamic coal cutting forces at the cutting bits, which excite the drum to vibrate and generate noise. Therefore, a straightforward noise control concept is force isolation, which aims to prevent the dynamic coal cutting force from being transmitted from the cutting bits to the main drum structure. In order to isolate the dynamic coal cutting force, the top layer of the connecting mass block (one inch in thickness), shown in Fig. 7(c), was given the properties of a rubber material. The rest of the connecting mass block shown in Fig. 7(b), the bit and bit holder system shown in Fig. 7(d), 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 bit 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.

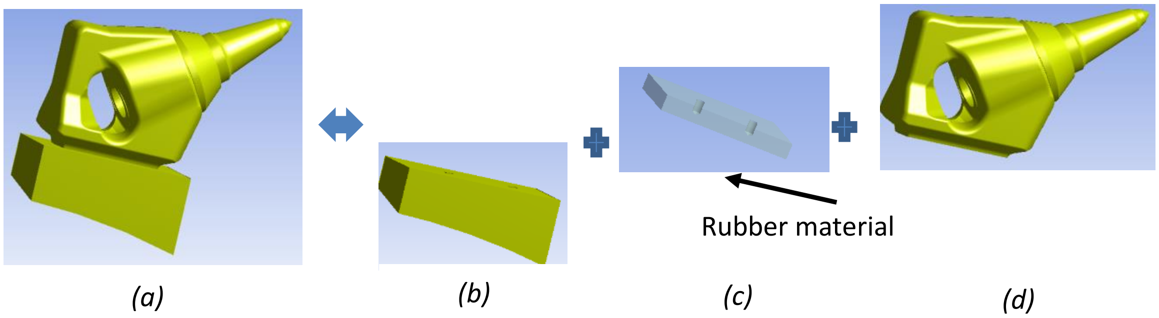


Figure 7: *(a)* Bit assembly, *(b)* connecting mass block, *(c)* rubber material, and *(d)* bit and bit holder.

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. Practically, the natural frequencies of the bit and bit holder system can be adjusted by using different rubber materials. In this study, a practical industrial rubber material was used to evaluate the effect of the bit isolation concept on the sound radiation, and a significant sound power reduction (around 25.9 dB(A)) was achieved. However, after discussing this concept with cutting drum design engineers, it was concluded that this concept is not suitable for the cutting drum case due to the extreme working environment, and bit isolation would probably cause some durability and cutting performance issues.

B. Damping treatment

Previously conducted experimental modal analysis on a newly manufactured drum indicated that the longwall cutting drum is very lightly damped [7]. 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 [8]. Due to the small damping ratio, there are many sharp peaks in the predicted sound power level spectra, which are shown in Fig. 4 and in the previous study [8]. Those peaks observed in the sound power level spectra can be suppressed by increasing the damping ratio of the drum. The effect of damping treatment on the predicted overall sound power level of the noise radiated by the longwall cutting drum is evaluated in this section.

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. The overall sound power level reductions for the two cases are given in Fig. 8, where it is shown that promising overall sound power level reductions can be achieved by increasing the loss factor (a 3.3 dB(A) reduction for a 0.02 loss factor and a 5.2 dB(A) reduction for a 0.03 loss factor).

Despite these reductions, the damping treatment concept is not an effective noise control strategy for the longwall cutting drum. One of the concerns is that it is not practical to perform damping treatment on the whole cutting drum. Performing damping treatment on the outer vane segments, which contribute the most to the total noise radiation as seen in the vibro-acoustic modeling and analyses section, might be much easier and more practical. However, by applying damping 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. Practically, the maximum reduction cannot be achieved. The largest reduction is approximately 3 dB(A), due to the fact that the noise generated by vibration of the outer vane segments accounts for roughly 50% of the total noise radiated by the whole drum, as shown in Fig. 6. Another concern is that the cutting drum will be covered with wet coal when it is in operation, and the cutting drum will also be worn after a certain period of use. How these changes may affect damping is not known. To examine these concerns, another experimental modal analysis was performed on a used longwall cutting drum. For the test on the used drum, coal particles were wedged between the vanes and the bit holders, and could not be removed. This test revealed that the used drum had much higher damping than a newly manufactured cutting drum.

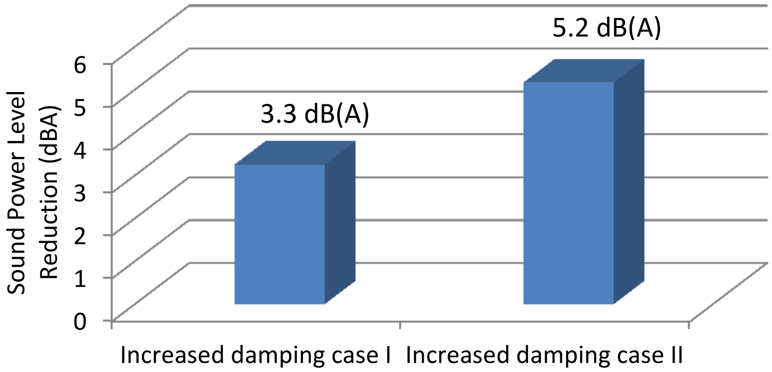
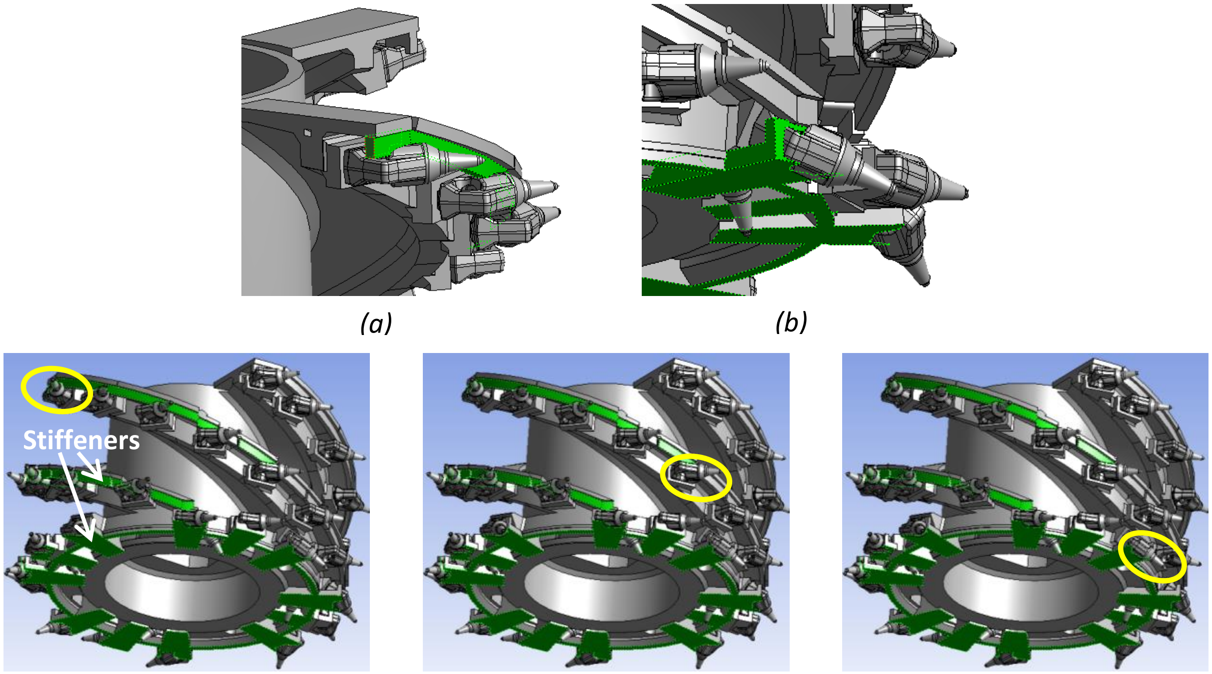


Figure 8: Sound power level reduction resulting from increasing the damping ratio.

C. Structural modification

The predicted sound power level spectrum has two dominant characteristics as described in Section 2. These characteristics directly relate the sound power level spectrum to the structure vibration, and provide an excellent basis for developing structural modifications for suppressing noise radiation. The first characteristic is that the sound power level will have 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 is to minimize the amplitude of the cutting bit dynamic deformation in the frequency range of interest 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. Reducing the number of modes of the outer vane segments in the frequency range of interest will reduce the noise.

Helical plates (1×2-inch cross section) were added to the model to connect the bit holders to the outer vane segments (refer to Fig. 9(a)) to stiffen both the cutting bit assemblies and the outer vane segments. The stiffeners provide additional support for the cutting bit assemblies, and they also provide T-shaped supports for the outer vane segments. The stiffeners also connect all the bit holder assemblies located on the same vane, which significantly suppresses the cutting bit assembly out-of-phase modes that occur along the vane. Modal analysis results of the modified cutting drum with stiffeners shows that the number of modes in the frequency range of interest (below 2 kHz) was reduced by around 70 (originally about 250 modes). For the cutting bit assemblies located on the face ring, there is no vane segment for the bit holder to be connected with. Therefore, an L-shape stiffener, highlighted in Fig. 9(b), was added for each bit located on the face ring instead of using the continuous plate stiffeners as used for the cutting bit assemblies located on the vanes.



(a) *(b)*

(c) *(d)* *(e)*

Figure 9: Stiffeners and excitations applied at different cutting bits.

Structural modification is the recommended noise control for the longwall cutting drum, due to its ease of implementation relative to other noise control concepts, and its ability to survive in the severe working environment of underground mines. Implementing structure modification involves manufacturing processes that are commonly used by the drum manufacturer. In order to assess the performance of the recommended structural modification, three different cases with excitations applied at different cutting bits were analyzed. The excitation locations for this analysis are highlighted with yellow cycles in Fig. 9c-e. During this research, an instrumented cutting bit was used to measure the dynamic coal cutting forces in an operating coal mine. For all three cases, the measured coal cutting forces were applied as the excitation. 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.10. From the simulation results, it can be seen that a promising sound power level reduction (approximately 3 dB(A)) can be achieved by performing structural modification of the longwall cutting drum.

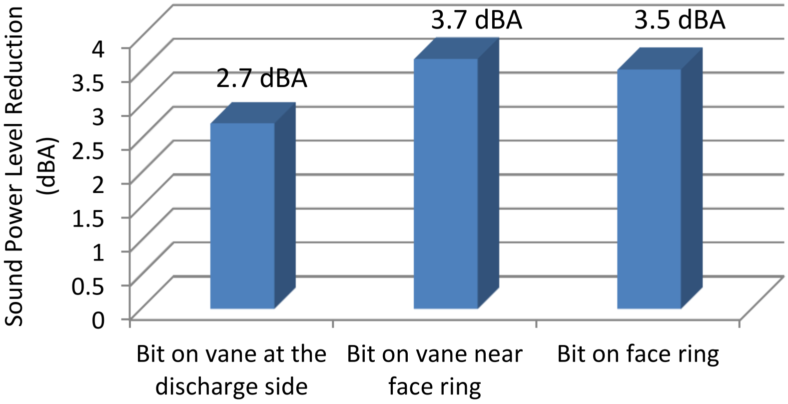


Figure 10: Sound power level reduction for different excitation cases.

4. CONCLUSIONS

The sensitivity of the sound power level radiated by a longwall drum to the directions of the excitation forces was determined through the use of a FEM-BEM model. The investigation results indicate that the sound power level will be high when the direction of the cutting bit dynamic deformation either aligns with or has a large component along the direction of the excitation force. A detailed panel contribution analysis was also performed in this study where the drum was divided into three parts: the cylindrical shell face, the inner vane segment faces, and the outer vane segment faces. The panel contribution analysis results revealed that the outer vane segments contribute the most to the total noise radiation.

Based on the analysis results, conceptual noise controls for the cutting drum were developed and evaluated numerically. The simulation results indicate that promising noise reductions (3 dB(A) or more) can be achieved by all three developed noise control concepts of the damping treatment, bit isolation, or structural modification. Due to the severe operating environment in longwall mines, the structural modification concept is believed to be the most suitable noise control strategy for the longwall cutting drum. The indicated 3 dB(A) reduction is significant because its implementation would mean a major reduction in the noise overexposure for longwall miners. Future research plans include the implementation and evaluation of drum structural modifications in an underground mine.

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