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SOUND RADIATION ANALYSIS OF A LONGWALL CUTTING DRUM

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ABSTRACT

Operators of longwall mining systems experience sound levels of 93-105 dB(A) and receive noise exposures that place them at risk of noise-induced hearing loss. To address the problem, the National Institute for Occupational Safety and Health (NIOSH*) Office of Mine Safety and Health Research (OMSHR) has conducted research to develop engineering noise controls for longwall systems. In previous field surveys, the sound radiated by the cutting drums was identified as a major hazard, especially considering their close proximity to the operators. Cutting drums are complex structures consisting of curved metal pieces welded together, and NIOSH has used modeling and simulation to characterize the acoustic properties of this structure. Based on a finite element (FE) model of the drum, the boundary element method (BEM) was used to predict the sound radiated from the vibrating drum due to an excitation force applied to one of the cutting bits. Simulations were used to examine the following with respect to the radiated sound power: (1) the ramifications of adding the welds to the model rather than assuming direct attachment between the metal components; (2) the effect of weld stiffness; (3) the relative contributions of the vanes and the cylindrical part of the drum; and (4) the sensitivity to the direction of the applied force. Parametric studies have shown that including the weld in the finite element model has a significant effect on the predicted sound power level, while varying the weld Young's modulus by 20% does not radically change the sound radiation. Panel contribution analysis indicates that the vanes contribute much more to the total sound power level, as compared to the cylindrical part of the drum. Consequently, it is expected that damping treatments would be most effective at controlling noise radiation if applied to the vanes rather than

to the cylindrical portion. Finally, case study results show that the sound power levels are most sensitive to the tangential and bending forces above 500 Hz. For frequencies below 500 Hz, the sound power level is most sensitive to axial and bending forces.

Key words: sound radiation, longwall cutting drum, weld

INTRODUCTION

Occupational hearing loss has been recognized as one of the most common occupational diseases for more than two decades [1], and the problem is particularly severe in the mining industry. 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 [2]. In order to address the problem, the OMSHR Hearing Loss Prevention Branch (HLPB) has been developing noise controls for mining machines. One of the current efforts of the HLPB has been focused on the development of noise controls for longwall mining systems, which generate sound levels from 93 to 105 dB(A).

Figure 1 shows a typical longwall mining system, mainly comprised of a shearer, an armored face conveyor (AFC), longwall shields, and a stageloader. The shearer, consisting of two cutting drums, cuts off the coal and pushes it to the AFC. The depth of each cut is around one meter. The ripped coal blocks are then transported to the stageloader by the AFC, which runs along the coal face. After the coal is crushed, it is loaded by the stageloader and placed 90 degrees to the coal face onto a belt conveyor to be taken out of the mine. Throughout this process, the powered self-advancing longwall shields are moved forward to provide continuous temporary roof support for both the shearer and the AFC as they advance. During operation, the shearer runs along the face back and forth between the headgate (the entry where the stageloader is located), and the tailgate (the entry at the other end of the AFC).

* The findings and conclusions in this report are those of the authors and do not necessarily represent the views of the National Institute for Occupational Safety and Health. Mention of any company name, product, or software does not constitute endorsement by NIOSH.

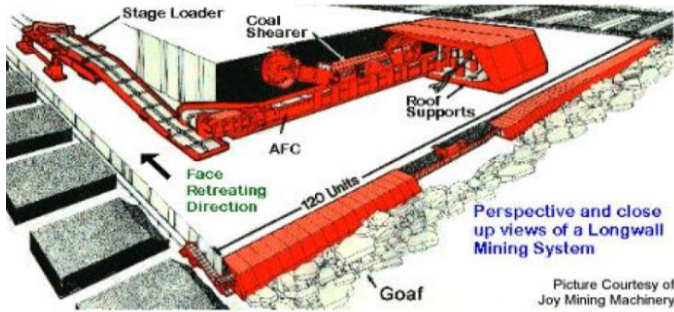


Fig. 1 - Schematic of a longwall system.

Previous studies indicate that the shearer [3-4] and stageloader [5,6] are the two major noise sources of longwall mining systems. In a miner noise exposure study conducted in 1994, shearer operators were reported to be exposed to a higher noise level of 93-105 dB(A), as compared with the 79-92 dB(A) of shield setters, and 82-99 dB(A) for headgate operators [3]. A sound pressure level of 96-101 dB was also reported to be generated by the longwall shearer in a review paper published in 2004 [4].

In this paper, the noise generated by a longwall shearer cutting drum has been analyzed. Because the longwall mining system is too large, heavy, and expensive to readily test in a laboratory, NIOSH researchers used numerical simulation for the purpose of analyzing the characteristics of the noise generated. Based on a FE model of the drum, the boundary element method was applied to predict the noise radiated from the vibrating drum due to an excitation force being applied to one of the cutting bits. Simulations were used to examine the following with respect to the radiated sound power: (1) the ramifications of modeling the welds; (2) the effect of weld stiffness; (3) the relative contributions of the vanes and the cylindrical part of the drum; and (4) the sensitivity to the direction of the applied force.

MODELING

Structural Model

The longwall shearer cutting drum examined in this study consists of a cylindrical body, around which four helical vanes are welded as shown in Fig. 2. The helical design of the vanes makes it easier for the shearer to push the ripped coal into the AFC as the drum rotates. The vane itself is also comprised of welded metal components. There are 44 pairs of bit holders and cutting bits welded around the cutting drum, with seven on the outermost edge of each vane, 12 on the outermost edge of the face ring, and 4 in the flange of the face ring. For modeling purposes, the force excitation was applied at the tips of the cutting bits in order to simulate the real coal cutting force. In this study, the force was exerted on only one of the cutting bits, which is sufficient to reveal the features of the radiated noise. For purposes of symmetry, a second cutting bit was added to the model 180 degrees away from the bit to which forces were applied. The bit is small and rigid in the frequency range used in this study, and the mass of the bit (1 kg) is very small as compared with the mass of the whole cutting drum (more than 4.5 tons). The small mass of the bit

only affects the local vibrational deformation, and the effect is minor. So as long as there is no excitation applied to any of the other 42 bits, excluding them does not sacrifice the accuracy of the structural FE model.

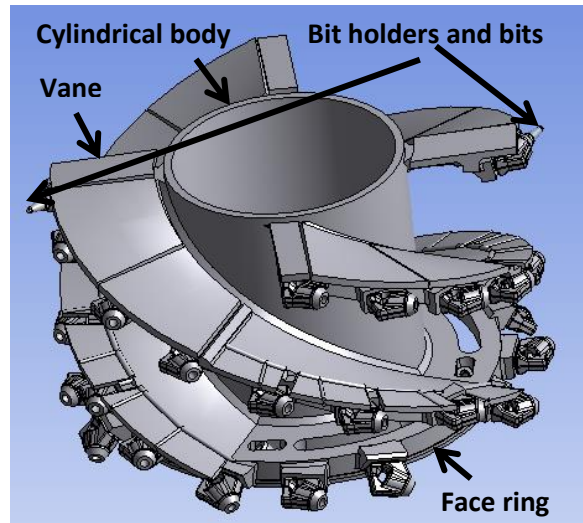


Fig.2 – Longwall cutting drum.

Using ANSYS, the main body of cutting drum was modeled as a single solid body, and the welds were represented by overlapping triangular bodies with coincident nodes at their interfaces. The welds between the cylindrical body and the four vanes were grouped together for the analysis because they have similar geometry and dimensions. Those welds were expected to have more effect on the low frequency results, because they act like the boundary conditions of the vanes. All of the other welds on the vanes and cylindrical body were categorized as another group because these welds were expected to affect the high frequency noise radiation more than the first group of welds. Most of the welds were modeled with triangular cross sections. During shearer-drum manufacturing, all welds are performed manually. The variations due to manual welding could result in discontinuities that could pose difficulties in modeling. Therefore, the effects of variations within the two weld groups on the sound power level were examined later in this study.

Sound Radiation Model

The modal analysis results from the FE model were imported into VA One (ESI) to perform a coupled structural-acoustic simulation. For this study, the air was represented using the BEM. The mode shapes of the drum were projected onto FE/BEM faces, as shown in Fig. 3, by conserving the nodal velocity. The effect of the generated sound pressure on the structural dynamic responses (acoustic loading) of the drum was included in the model, and the acoustic load was projected from the FE/BEM faces back onto the structural model. Small features of the FE/BEM interface (for example the bit holders) were not included in the model, because they have a negligible effect on the radiated sound. Under operating conditions, the cylindrical body is actually filled with other mechanisms such as the gearbox, so acoustic cavity

modes do not exist within the inside of the drum. To eliminate the effect of cavity modes on the sound radiation predicted by the model, two faces were added to the ends of the cylindrical part of the drum. The coal cutting force was simulated by applying a point force of 1 kN root mean square (rms) in each frequency band to the tip of a cutting bit.

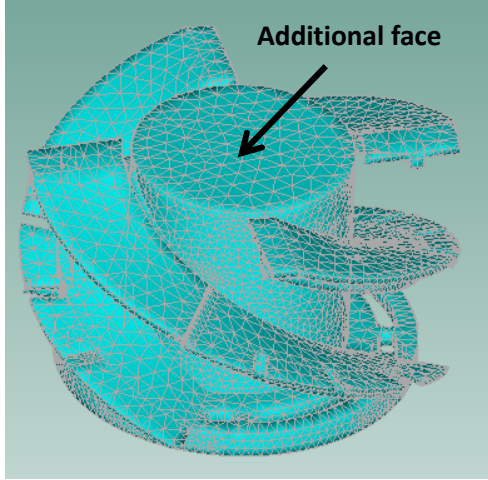


Fig.3 – FE/BEM interface used for vibro-acoustic analysis.

The calculation of the sound power level from the numerical model was based on the international standard ISO 3744, which specifies a method for determining the sound power level produced by a source. A rigid, infinite surface underneath the cutting drum is defined in the numerical model in order to create a hemispherical measurement surface. Based on modal testing results [7], the drum is a very lightly damped structure, so the sound radiated may have a sharp peak for each structure mode. In this study, a uniform 0.01 loss factor was applied as an approximation of the damping ratio obtained from the experimental modal analysis for the drum structure [7], and zero damping was assumed for the air. Considering the possible sharp variations in radiated sound energy, ten acoustical sensors were placed according to the microphone positions recommended in ISO 3744 for sources emitting discrete tones. The sound power level L_w in dB(A) was then calculated from the predicted A-weighted sound pressure levels using the following equation:

$$L_w = 10 \log \left(\frac{1}{10} \sum_{i=1}^{10} 10^{0.1L_{pi}} \right) + 10 \log(S) \quad (1)$$

where L_{pi} represents the sound pressure level of microphone i ($i = 1, 2 \dots 10$), and S is the area of the hemispherical measurement surface in square meters.

For all of the simulation cases, 1/n-octave-band analysis was applied to reduce the number of calculations and the time required to conduct the analyses. The predicted sound pressure level at the center of each frequency band was taken as the average level for that particular frequency band. If the frequency spacing is too coarse, it is possible to miss peaks and anti-peaks of the sound power spectra. According to a NASA report [8], assuming single-mode behavior, the greatest error that can result by missing a peak is given as

$$\Delta dB = 20 \log_{10} \left(\eta_{min} \left((1 - 2^{1/n})^2 + 2^{1/n} \eta_{min}^2 \right)^{-1/2} \right) \quad (2)$$

where η_{min} represents the minimum loss factor. As mentioned previously, a uniform loss factor of 0.01 was applied throughout the studied frequency range. When the loss factor is substituted into the above equation, for 1/72-octave-band analysis, the largest error due to a missed peak is about -2.9 dB, and it is around -0.95 dB for 1/144-octave-band analysis. So in this study, the analyses were conducted in 1/144-octave bands because the potential errors due to missing a peak are less than 1 dB.

RESULT AND DISCUSSION

Baseline Sound Power Level

For the baseline case, a point force of 1000 N rms in each frequency band was applied to the tip node of a cutting bit along its axial direction as shown in Fig. 4. The FE/BEM interface as shown in Fig. 3 was considered as an elastic surface, and within the simulation all of the welds were defined to have the same material property as the main body of the drum, which is made of steel. The force definition and material properties mentioned later in this study will be used for all of the following numerical studies unless otherwise specified. The sound power level predicted using the above force and material properties is shown as Fig. 5. Due to the low damping ratio of the structure, numerous sharp peaks are observed in the obtained spectrum, especially for frequencies less than 1 kHz. These results suggest that adding damping treatment could be a feasible way to reduce the noise.

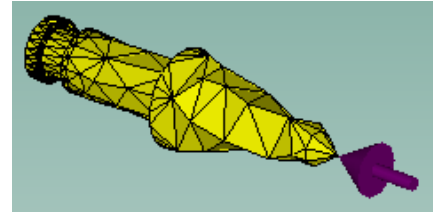


Fig.4 – Axial excitation force as applied to the cutting bit for the baseline analysis.

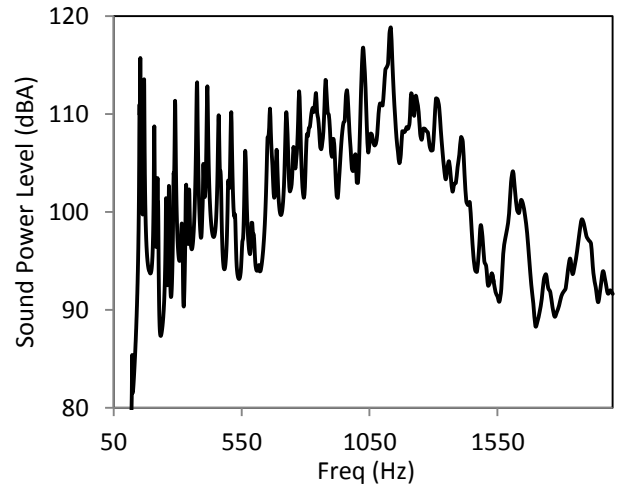


Fig.5 – Baseline sound power level

Effect of Welds

The welds were categorized into two sets based on their geometries, dimensions, and locations. The major welds connecting the four vanes to the cylindrical body of the drum were taken as set-1 as shown in Fig. 6(a). All the other welds on the vanes and the cylindrical body as well as those connecting the bit holders to the cutting drum, as shown in Fig. 6(b), were grouped as set-2. The effects of those two sets of welds on the noise radiation were studied separately in order to determine the extent to which they have different effects on the predicted sound power level for different frequency ranges.

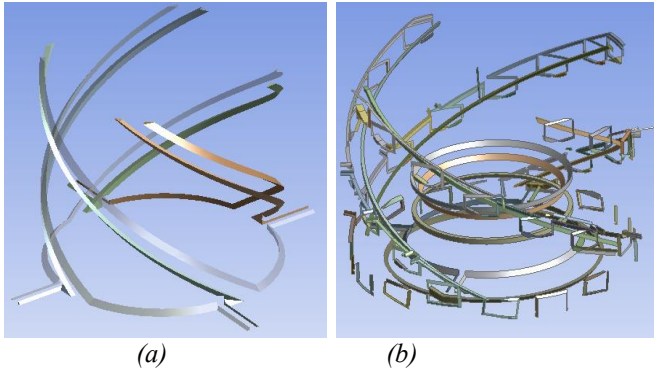


Fig.6 – (a) welds set-1, consisting of just the major welds on the drum; (b) welds set-2, consisting of all of the remaining welds.

First, the effect of adding the welds to the model rather than assuming direct attachment between the four vanes and the cylindrical body was studied. Weld set-1 was excluded intentionally from the model when performing both the modal analysis and the structural-acoustic simulation, in order to evaluate the effect of including the welds on the predicted sound power level by comparing with the baseline results. The obtained sound power level was compared with the baseline case results, and the difference between them is shown in Fig. 7. As expected, this group of welds has the greatest effect on the sound power level at low frequencies. The results indicate that adding the welds between the vanes and cylindrical body has a significant effect on the predicted sound power level, especially for frequencies below 500 Hz where the magnitude of the difference for several frequencies is over 20 dB(A). It is observed that adding welds between the vanes and cylindrical body may cause a maximum of 10 dB(A) variation in sound power level for frequencies above 500 Hz, which is also significant. Based on the above results, the incorporation of Weld set-2 to drum is also believed to have a significant effect on the sound power level. This numerical comparison is not included in this paper.

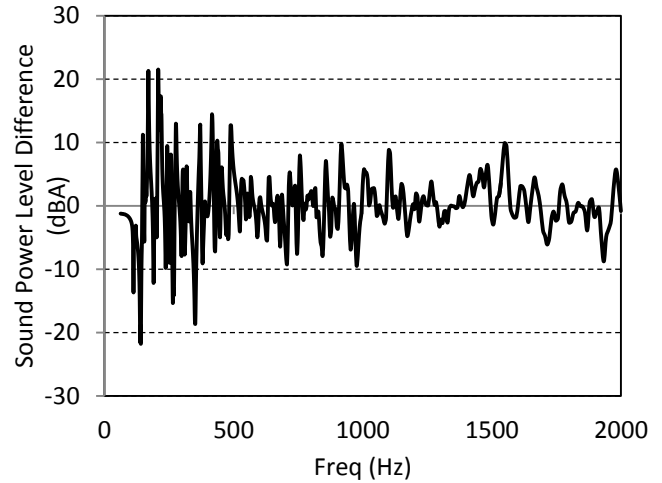


Fig.7 – Effect of adding welds on the sound power level radiated by the drum.

The Young's modulus of Weld set-1 was changed by $\pm 10\%$ to study the effect of the weld stiffness on radiated sound. The difference between the calculated sound power level spectra of the 110% and 90% Young's modulus cases is shown in Fig. 8. Similar to the previous results, changing the material properties of Weld set-1 has more effect on the low frequency sound power level results as compared with the effect on the high frequency results. The magnitude of the difference is less than 2 dB(A) at most frequencies, except for frequencies around 200 Hz and 400 Hz which have differences of around 4 dB(A).

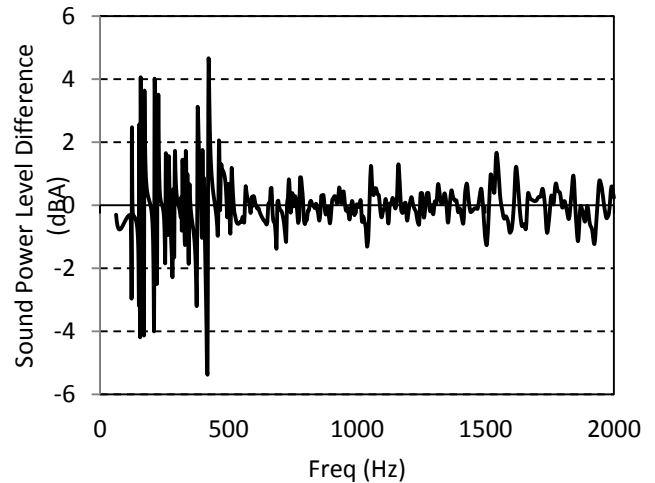


Fig.8 – Effect of stiffness of welds set-1 .

Similarly, the Young's modulus of Weld set-2 was also changed by $\pm 10\%$ to study the effect of their stiffness on radiated noise. The difference between the predicted sound power levels of the two cases with different Young's moduli is given in Fig. 9, which shows that the magnitude of the difference for most frequencies is less than 3 dB(A). Comparing Fig. 8 with Fig. 9, it can be seen that the second group of welds has more effect on the high frequency sound power level results than the first group of welds does.

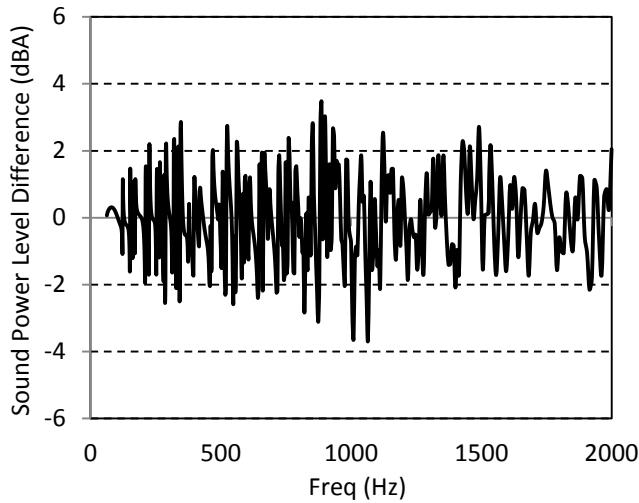


Fig.9 – Effect of stiffness of welds set-2.

The above parametric studies show that including the welds in the FE model and the structural-acoustic simulation has a significant effect on the sound radiation, which suggests that care must be taken to model the welds properly. On the other hand, changing the weld's Young's modulus does not radically change radiated noise, but it is not expected that modifications of the drum will achieve much more than 3 dB(A) reduction so a 20% change of Young's modulus could be important.

Panel Contribution Analysis

The longwall cutting drum was a lightly damped structure, as mentioned previously, and a 0.01 loss factor was applied as an approximation of the damping ratio obtained from the experimental modal analysis. Therefore, it might be feasible to reduce the noise radiation by adding damping treatments to the entire drum. However, considering the costs, it is better to add damping treatments to only the part of the drum that contributes the most to the radiated noise. Panel contribution analysis was conducted to identify which part of the drum radiates the most noise. In this study, the FE/BEM interface was divided into two parts: the vane face as shown in Fig. 10(a) and the cylindrical body face as shown in Fig. 10(b). Two additional cases besides the baseline one were considered. Only the vane face was considered to be elastic for one of the two cases, and for the other case only the cylindrical body face was defined to be elastic. Defining faces as either elastic or rigid made the panel contribution analysis possible, because only faces defined as elastic can radiate noise.

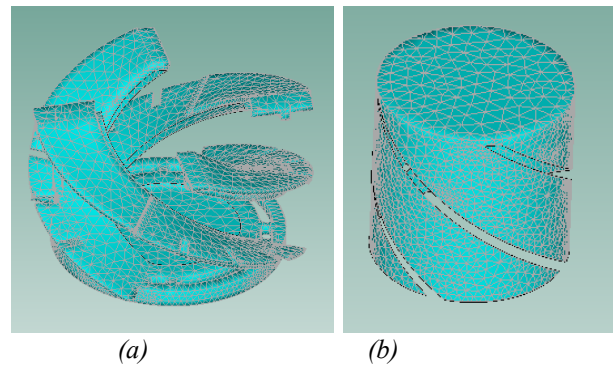


Fig.10 – (a) vane face; (b) cylindrical body face.

The predicted sound power levels for those two cases as well as the baseline case results, where all the FE/BEM faces are considered as elastic, are shown in Fig. 11. It can be seen that the noise radiated from the vane face and the baseline curve almost overlap with each other, and they are at least 10 dB(A) higher than the sound power level generated by the cylindrical body face except for the results around 400Hz, 700Hz, and 1500Hz. The comparison reveals that the vanes contribute much more to the total noise than the cylindrical body does. Consequently, it is expected that damping treatments would be most effective at reducing noise radiation if applied to the vanes rather than to the cylindrical portion of the drum.

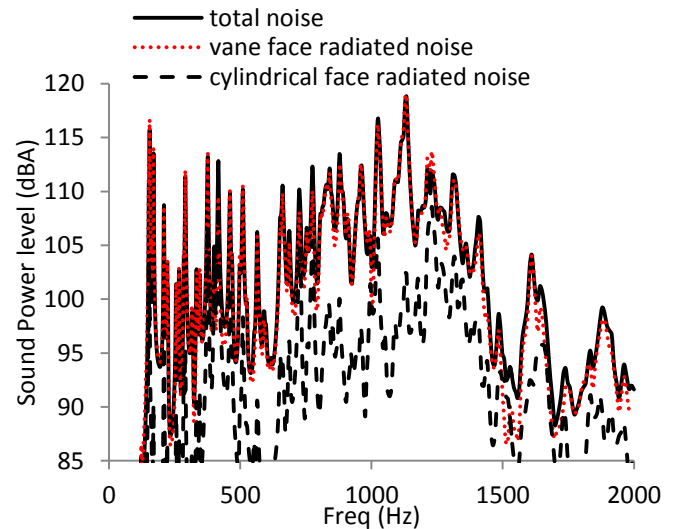
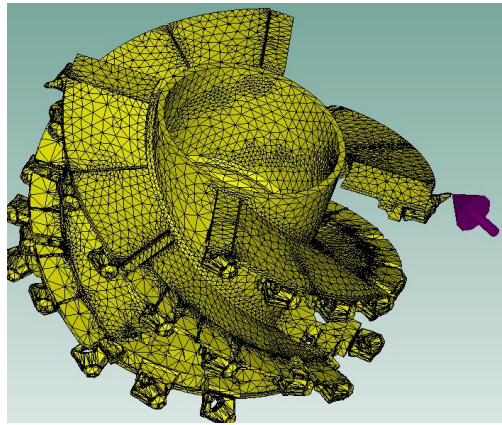


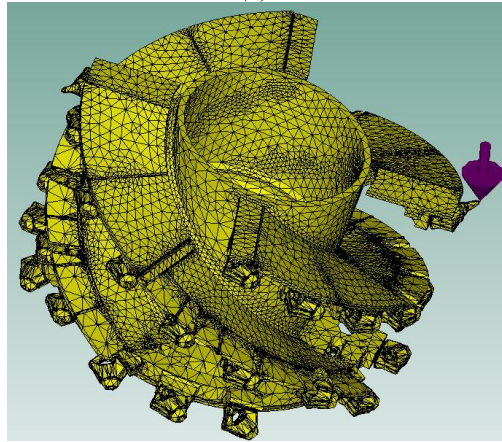
Fig.11 – Panel contribution analysis

Sensitivity to Directions of Force

The direction and magnitude of the coal cutting forces are constantly changing when the longwall mining system is operating. As a result, the characteristics of the noise radiated from the cutting drum also change as it rotates. In this section, the sensitivities of the sound radiation to the directions of the excitation force were analyzed. In order to define the directions of force, a local coordinate system was established at the tip of the cutting bit. Forces applied along the three axes of the local coordinate system were defined as the axial force as shown in Fig. 4, the tangential force as shown in Fig. 12(a), and the bending force as shown in Fig. 12(b).



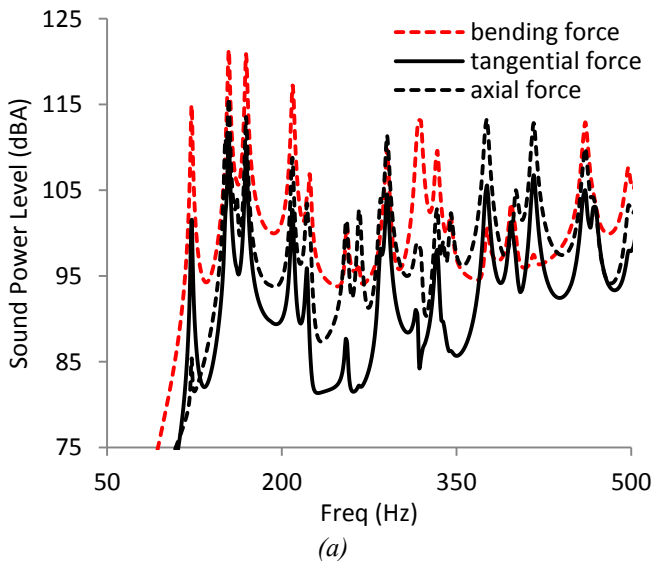
(a)



(b)

Fig.12 – (a) Tangential excitation force; (b) Bending excitation force.

One analysis was run for each of the force components. In each analysis, the drum was excited by the axial, tangential, or bending force with the other components set to zero. The excitation forces in each direction were applied at the same node for all three cases, and they all had the same rms value of 1 kN in each frequency band. The predicted sound power level spectra for each force direction are shown in Fig. 13.



(a)

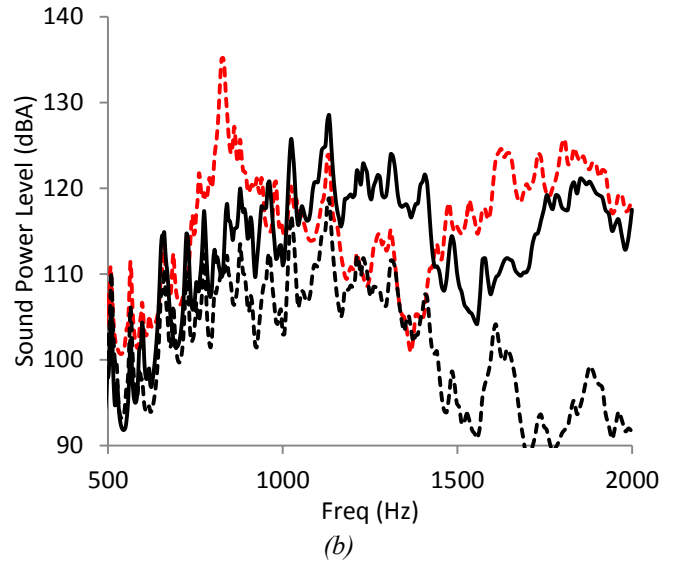


Fig.13 – Sensitivity analysis for (a) low frequencies up to 500 Hz and (b) high frequencies above 500 Hz

A comparison of the results for the cases of the three different excitations directions suggests that, except for a few peaks, below 500 Hz the noise radiation is more sensitive to the axial and bending forces than to the tangential force, as shown in Fig. 13(a). For most of the frequencies above 500 Hz, the sound power levels for the axial force case are lower than the sound power levels for the tangential and bending force cases, as shown in Fig. 13(b). It can also be observed from Fig. 13(b) that the tangential force case generates the highest sound power levels for frequencies between 1040 and 1430 Hz, and that the bending force makes the highest sound power levels at all other frequencies.

SUMMARY

An FE model of a longwall cutting drum was created, where the major part of the drum was modeled as a single solid body and the welds were represented by overlapping triangular bodies with coincident nodes at their interfaces. Based on this FE model, a coupled structural-acoustical model was also established with the help of the BEM to predict the sound radiated from the vibrating drum due to an excitation force applied to one of the cutting bits.

Parametric studies show that including the weld in the FE model has a significant effect on the predicted sound power level, which suggests that care must be taken to model the welds properly. On the other hand, varying the weld Young's modulus does not radically change the sound radiation. However, it is not expected that modifications of the drum will achieve much more than 3 dB(A) noise reduction, so 20% changes of the weld Young's modulus could be important. Panel contribution analysis indicates that the radiated noise in the frequency range of interest is dominated by the motion of the vanes. Consequently, it is expected that damping treatments would be most effective at controlling noise radiation if applied to the vanes rather than to the cylindrical portion. The numerical results also show that tangential and

bending forces are of primary importance in accurately predicting radiated noise in the frequency range of interest.

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