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Sound Radiation Modeling and Correlation of a Longwall Cutting Drum

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ABSTRACT

Longwall mining systems produce around 50% of the coal from underground mines in the U.S. The operators of these systems experience 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 cutting drums were identified as a major noise source, especially considering their close proximity to the operators. Because the longwall mining system is too large, heavy, and expensive to readily test in a laboratory, researchers from the National Institute for Occupational Safety and Health (NIOSH) used numerical simulation to evaluate potential noise control treatments. In this paper, hybrid finite element/statistical energy analysis (hybrid FE/SEA), finite element (FE), boundary element methods (BEM), and the fast multipole method (FMM) BEM were compared for their ability to predict the noise radiated from the vibrating drum structure. The comparison indicated that the BEM results were the most accurate, and a reasonable correlation between the BEM predictions and the measured data in a shop environment was obtained. In addition, the modeling of the BEM is easier because only a surface mesh is needed, and the BEM model can be easily converted to FMM BEM when the analysis goes to higher frequencies. So BEM was chosen as the best solution for the further analysis of the longwall cutting drum sound radiation.

1. INTRODUCTION

A. Problem definition

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). Previous studies indicate that the shearer [1-2] is one of the major noise sources of longwall mining systems. In a noise exposure study conducted in 1994 [1], shearer operators were reported to be exposed to a noise level of 93-105 dB(A). A sound level of 96-101 dB was also reported to be generated by the longwall shearer in a review paper published in 2004 [2]. This level of noise places operators of longwall mining systems at great risk of noise-induced hearing loss. In this context, the Hearing Loss Prevention

Branch (HLPB) of the National Institute for Occupational Safety and Health (NIOSH) is conducting a research project to develop noise controls for longwall mining systems.

Figure 1 shows a typical longwall mining system, 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 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). All of the major components of the longwall mining system generate noise, but the cutting drums are a major noise source in close proximity to the operator.

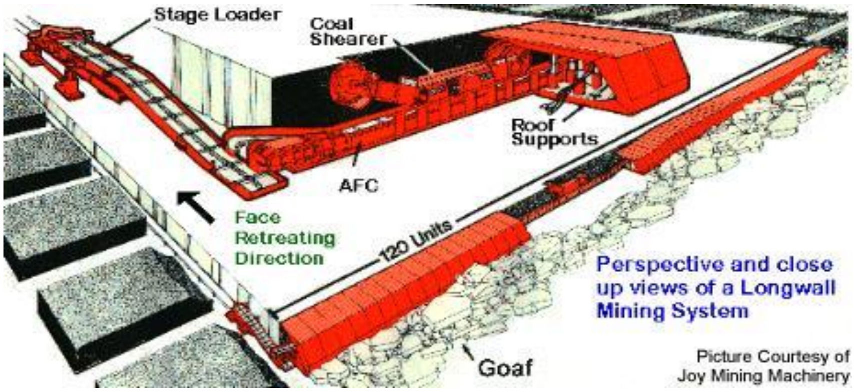


Figure 1: Schematic of a longwall system.

B. Objective

In this paper, only the longwall shearer drum was considered. 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 7 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. The noise radiated from the vibrating drum structure were studied using all of the hybrid finite element/statistical energy analysis (Hybrid FE/SEA), finite element (FE), boundary element method (BEM), and fast multipole method (FMM) BEM analyses, based on a validated drum FE model [3]. The numerical vibro-acoustic modeling approaches for the cutting head of a longwall shearer were compared. The strengths and weaknesses of the different modeling approaches are discussed. Finally, the sound pressure level spectrum predicted using the BEM are compared with the measured sound pressure level spectrum. This study was undertaken in order to understand the limits of the available modeling methods and the mechanisms of acoustic radiation of the longwall cutting drum. With validated models and insight into the primary contributors to the radiated noise, design guidance may be provided to mining equipment manufacturers.

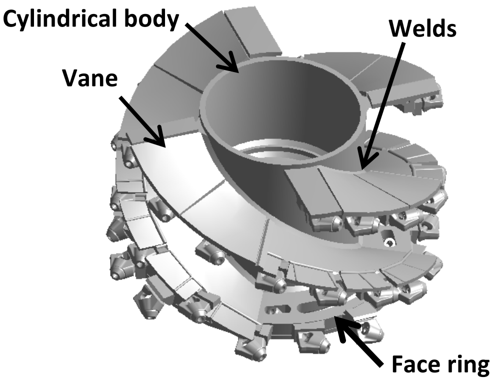


Figure 2: Structure of the longwall cutting drum.

2. VIBRO-ACOUSTIC MODELING APPROACHES

A. Overview of the Technologies

There are several technologies available to analyze potential noise controls. The frequency range of interest plays a role in determining which technologies should be used. Typically, at the lower frequencies, deterministic models are used. In these models, interactions from all portions of the model are considered together. At high frequencies, the dynamic complexity of the motion is such that tracking all the interactions is too computationally expensive, but statistics about the behavior provide useful information. In this analysis of the longwall shearer cutting head, the focus is on the lower frequency region, so the emphasis was on deterministic methods. In this case, the structural model will always be a deterministic model. The structural vibration was modeled with structural finite elements. Next, the structure was coupled to various models of the acoustic space. All models of the fluid in the acoustic space assume that the fluid is governed by the acoustic wave equation, which can be converted in the frequency domain to the Helmholtz equation. The different technologies that were considered to model the fluid are described in the following sections.

In operation, the longwall shearer cutting drum vibrates due to the cutting loads. The vibrations radiate sound into the mine. The physics of the structural-acoustic coupling require the modeling of three mechanisms: (1) the acoustic radiation from the structural motion, (2) the impedance of the fluid pushing back on the structure, and (3) the sound that builds up in the mine and pushes back on the structure. In the case of mining equipment, the structure is typically heavily built and the effects of mechanisms (2) and (3) are not expected to be significant. This provides some flexibility with acoustic analysis. First, the mine need not be modeled. Instead, an infinite acoustic space is considered. The resulting acoustic radiation will be affected somewhat by the mine. However, the mine dimensions will be different at different mines and will change as mining progresses. For this reason, the mine is modeled as an infinite space (this will primarily affect mechanism (3)). It is worth noting that the measurement of radiated sound power is a significantly better variable than using radiated sound pressure levels at specific locations when characterizing equipment noise. It is because sound power is independent of the surroundings of the source and therefore, is an absolute measure of the sound emitted by the device. Sound pressure is affected by the environment and will change when moving the machine from one environment to the other.

B. Hybrid Finite Element / Statistical Energy Analysis

With hybrid finite element/statistical energy analysis, a deterministic method (finite element analysis) is coupled to a statistical method (statistical energy analysis). The hybrid method is described in several papers [4-6]. This particular implementation of the hybrid FE/SEA method specifically involves coupling a FE structural model to an SEA acoustic model. In this case, the acoustic space is an infinite space (as opposed to an enclosed cavity). The structure will feel the effect of the fluid and will radiate sound (mechanisms (1) and (2) from the overview above). The SEA model of the fluid structure interaction allows for a few more approximations than the other methods. The exact approximations will depend on how the surfaces are meshed. The surfaces are broken up into simply connected regions (called faces). The faces are the key to the hybrid coupling and where the assumptions are made. The assumptions made on each face are: (1) each face is assumed to be uncorrelated from the 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 assumption (1), but somewhat due to assumption (3)). 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. However, even with these assumptions, the hybrid method was developed for and should have greater accuracy in the mid-frequency region from 500 – 2000 Hz [5]. The hybrid method can be as much as two orders of magnitude faster than some of the other methods.

C. Finite Element Analysis

Acoustic finite elements can be coupled to the structural FE model. With acoustic FE, the cavity—in this case the mine—is meshed. Since the cavity is meant to be an infinite space, the cavity mesh can be large. The cavity mesh will be stopped at some point. At the outer boundary of the cavity mesh, the radiation boundary condition can be applied in three different ways: (1) as infinite acoustic elements, (2) as an SEA semi-infinite space (as in the hybrid approach), or (3) as an impedance boundary condition using the natural impedance of the fluid. The first two of these methods can be very accurate, while the third approach is a bit of an approximation, but can provide simple, quick, and accurate results. The biggest drawback of the acoustic FE approach is the effort required to make the cavity mesh. This is particularly true if there are thin surfaces on the structure. Depending on the model and the frequency range, the FE mesh can become large as well.

D. Boundary Element Analysis

Acoustic BEM analysis of a cavity (or infinite space) is an element-based analysis where the surface of the fluid is meshed with surface elements but the volume of the fluid is not meshed. This method is typically the easiest and quickest modeling approach to set up. The downside is the analysis time. A bit of discussion about the implications of a surface mesh can explain the higher analysis cost. With only a surface mesh, each element must have a direct impact (through the fluid) on every other element in the mesh (this makes for a fully populated matrix). With a volume mesh (as in acoustic FE), each element only directly impacts adjacent elements (this makes for a very sparse matrix). The BEM matrix will be smaller but full, while the FE matrix is larger but very sparse. The BEM approach considers all the interactions, reflections, and all details of the geometry. It can account for all of the mechanisms that act between the structure and the fluid. All of the methods can achieve adequate accuracy, but the BEM makes the fewest assumptions and is typically the most robust analysis method in practice. The downside of the BEM is that large models take too long to solve. This effectively caps the BEM frequency range.

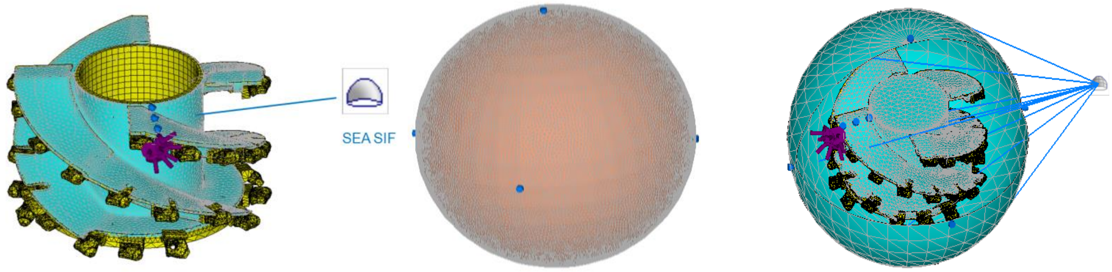
E. Fast Multipole Method/BEM

The fast multipole method (FMM) is a form of BEM that can solve significantly larger problems [7]. Briefly, the BEM equations are streamlined by using a multi-level multipole method to simplify the BEM connectivity. When elements are a large distance from each other, the equations are simplified by grouping elements together and looking at the net effect of the group on distant elements. Using a tiered hierarchical manner, the BEM equations can be simplified. Further speed improvements come from using an iterative solver with a highly tuned pre-conditioner. The combination of these methods can provide 2-3 orders of magnitude faster solutions. The downside is that results are a bit more approximate and that the speed improvement tends to be lost when solving a coupled fluid-structure problem. With heavy machinery radiating into the surrounding air, the impact of the fluid structure coupling should be minimal and the FMM will provide a solid method to analyze higher frequency as compared to using BEM alone.

3. RESULTS AND DISCUSSION

A. Initial Investigations

The initial investigations were used to compare the different methods, analyzing the cutting drum with a force excitation. The models used for the hybrid, acoustic FE, and BEM analyses are shown in Fig. 3. The BEM and the FMM BEM share the same model. For all four models, a 0.5% damping ratio was used for the cutting drum structure throughout the frequency range. Because the 0.5% damping ratio is typically used when we know very little about the structure; and it is also a recommended value in VA ONE software.



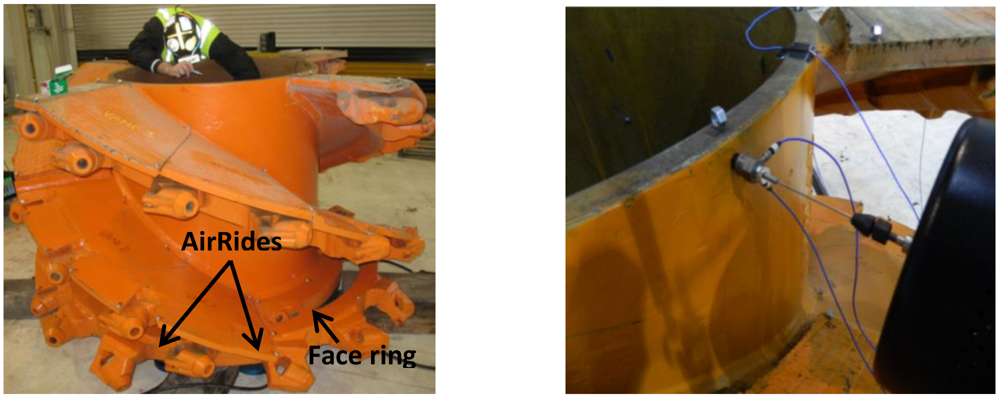
(a) *(b)* *(c)*

Figure 3: Numerical models of the structural FE mesh: (a) with SEA Semi-infinite fluid (SIF) acoustics, (b) surrounded by acoustic FE mesh of the fluid out to a sphere with radiation boundary conditions, and (c) with BEM radiation mesh on the surface and a pressure recovery spherical surface at the microphone locations.

B. Detailed Modeling and Testing

1. Summary Validation Testing

The test was conducted in the machine shop of a collaborating mine, where there was a certain amount of ground vibration and background noise. The cutting drum was placed with the face ring down on nine equally spaced inflatable rubber supports (AirRides, as shown in Fig. 4(a)). The AirRides were inflated to a pressure of approximately 655kPa, at which each AirRide has a spring rate of 2.27x10^5N/m. For this setup, the rigid body mode caused by the flexibility of the AirRides is less than 3.4 Hz, with the total mass of the cutting drum being over 4.5 tons. Meanwhile, the natural frequency of the first cutting drum flexural mode is approximately 120 Hz, which is well-separated from the 3.4 Hz rigid mode. Thus, the effect of the supports on the shop testing results can be ignored. Placing the cutting drum on the AirRides can also isolate the ground vibration. However, there is no effective way to cancel the background noise. Therefore, tonal forces around the natural frequencies of the cutting drum rather than broadband excitation were applied for this test. By applying forces at the natural frequencies of the drum, where the drum radiates the most noise, the effects of the background noise on the measured sound were minimized. Based on the measured signal, the cutting head radiated noise level is at least 10 dB higher at its natural frequencies than the background noise. The excitation was chosen to be placed at a point on the cylindrical body. An electromechanical shaker, shown in Fig. 4(b), with a maximum input force of 489 N was used as the excitation mechanism. This excitation location was determined from a pre-test analysis which showed that this location provided sufficient excitation of all the modes in the frequency range of interested.



(a) *(b)*

Figure 4: (a) Drum sitting on AirRides (b) shaker providing tonal forces

The sound pressure level of the noise generated by the cutting drum vibration was measured using seven microphones, as shown in Fig. 5. Microphones one (M1) to six (M6) were placed three feet above the ground and away from the outermost edges of vanes. The seventh microphone was placed three feet above the top center of the cylindrical body. The measured data were used to validate the numerical sound radiation models. Accelerometers were also mounted on the cutting drum to measure the structural vibration. The accelerations of two points, one on the cylindrical body and the other on the vane as shown in Fig 6(a), were compared with the modeled results. The same two points are used for all modal frequencies, and it is sufficient in the frequency range of interest.

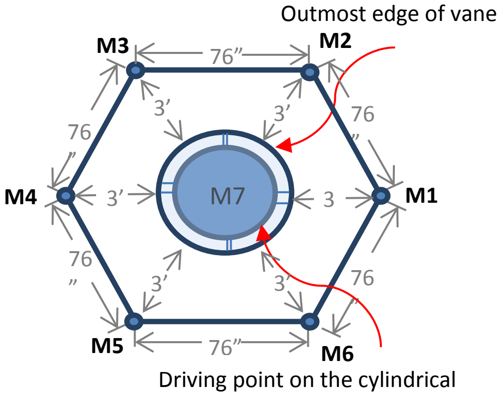
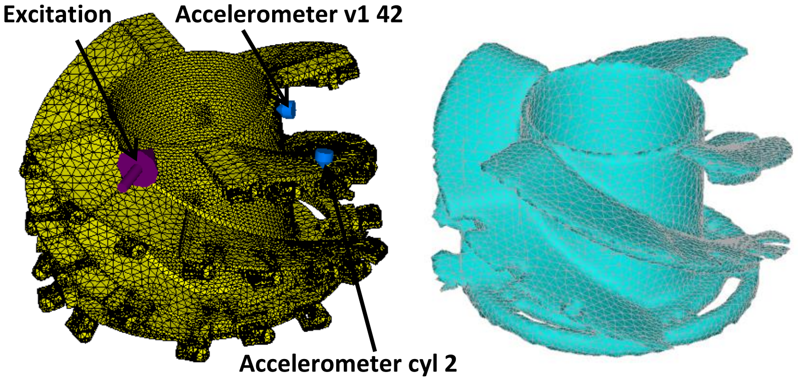


Figure 5: Microphone layout

2. Summary of the Structural FE and BEM Models

As mentioned previously, there are a total of 44 cutting bits on the cutting drum. The bit is small and therefore rigid in the frequency range used in this study. The mass of the bit (1 kg) is also very small as compared with the mass of the entire cutting drum (greater than 4.5 tons). The small mass of the bit only affects the local vibrational deformation, and the effect is minor. Therefore, as long as there is no excitation applied to any of the 44 bits; excluding them does not sacrifice the accuracy of the structural FE model. In reality the forces are coming from the bits, and the modeling setup in this paper is only applied to the test case described in this paper. 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 finite elements (see Fig. 6(a)). The arrow represents the excitation and the other two marks indicate the accelerometers.



(a) *(b)*

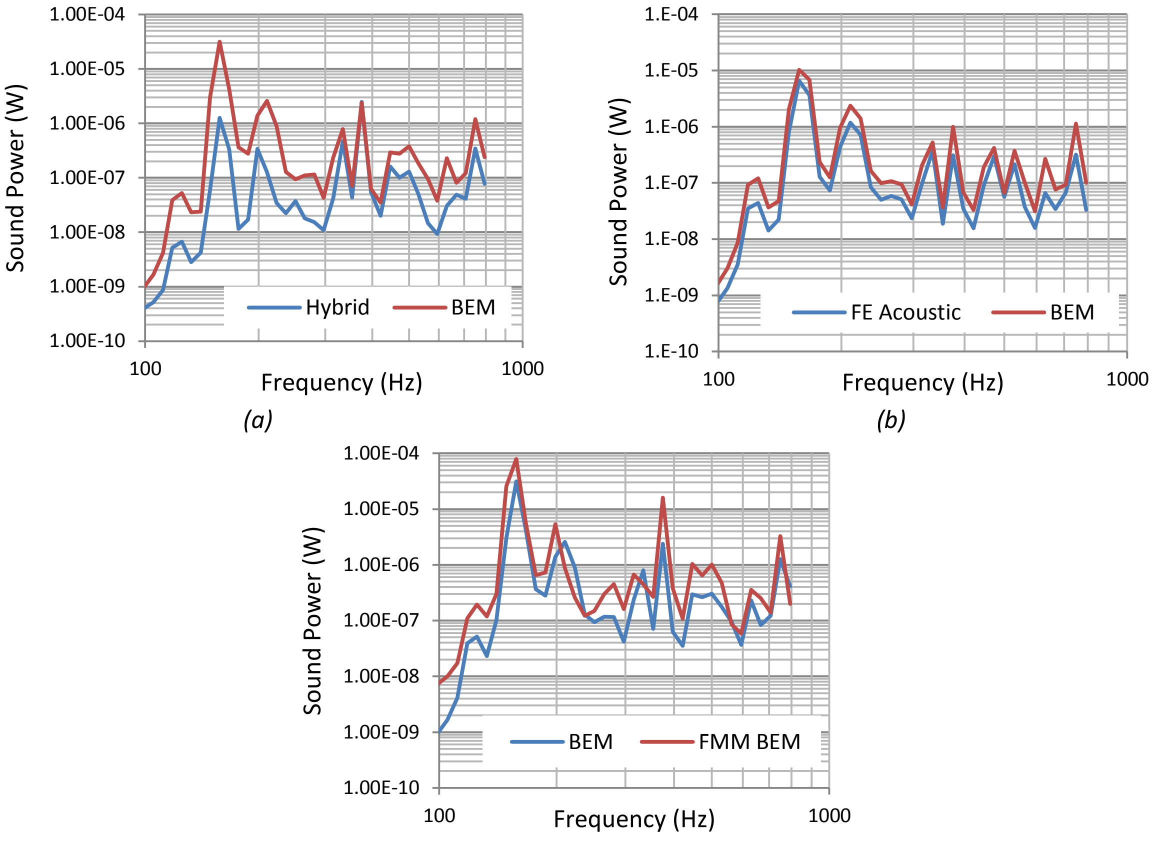
Figure 6: Longwall cutting drum: (a) Structural FE model. (b) BEM fluid surface mesh.

The surface mesh of the BEM fluid was created by shrink-wrapping the structural mesh (see Fig. 6(b)). This mesh has 10,600 elements and should be adequately meshed for analysis to 2,000 Hz (at 4 elements per wavelength). A BEM fluid with standard air properties (speed of sound of 343 m/sec and a fluid density of 1.21 kg/m^3) was then attached to the surface mesh in Fig. 6(b).

C. Results

1. Initial Investigation

The predicted radiated sound power is shown in Fig. 7. The results differ slightly as different force locations were used. However, in each of the plots the BEM analysis data is used for a standard of comparison. In Fig. 7(a), the results from hybrid FE/SEA model are compared with the results from the BEM model. The geometry of this problem is not ideal for the hybrid approach. This is primarily because the fluid surfaces of the vanes are modeled with a surface that wraps over the thick steel vane. This gives two surfaces that are close together, while the hybrid method ignores the curvature and flattens the surface. The hybrid method is also known to be mainly good for middle frequency range applications [5, 8]. Thus, the hybrid results are observed to be consistently lower than the BEM results. In Fig. 7(b), the acoustic FE results are compared to the BEM results. It can be observed from the comparison that the BEM results are consistently higher than corresponding FE acoustic results, which is due to approximations with the radiation boundary condition for the FE analysis. Further, there are also some additional meshing requirements to model the volume mesh of the fluid region, when performing FE analysis. The BEM and acoustic FE results for these specific models did not show significant differences in run-time. In Fig. 7(c), the FMM BEM is compared to the standard BEM approach. This model does not show the real advantage of FMM BEM, which allows significantly larger problems to be solved (such as solving to significantly higher frequencies). FMM BEM is most useful at significantly higher frequencies. For the studied problem, the hybrid and the FMM models took approximately 5 times as long to solve as the BEM approach. The acoustic FE model was about 20% faster than the BEM, but the modeling effort was greater.



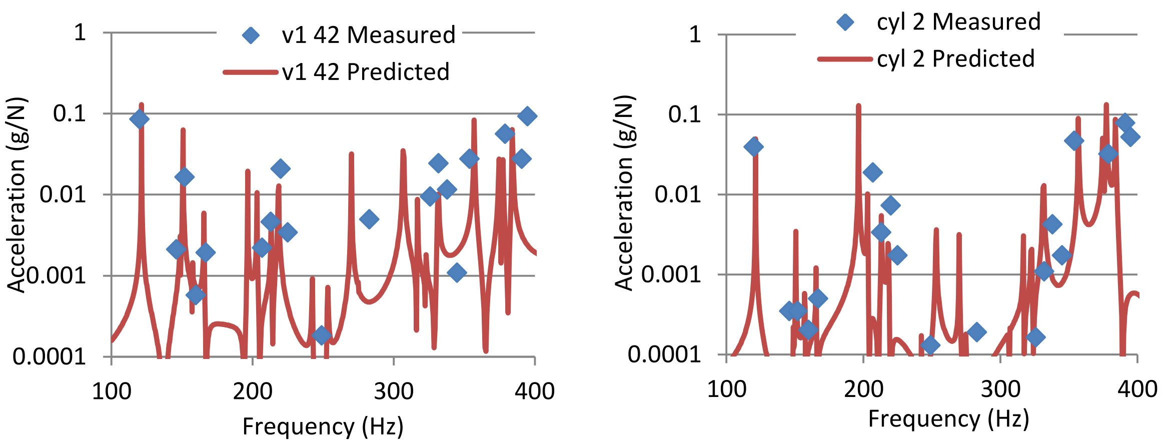
(a) *(b)*

(c)

Figure 7: Predictions of the radiated sound power. (a) FE/SEA versus BEM, (b) Acoustic FE versus BEM, and (c) BEM versus FMM BEM.

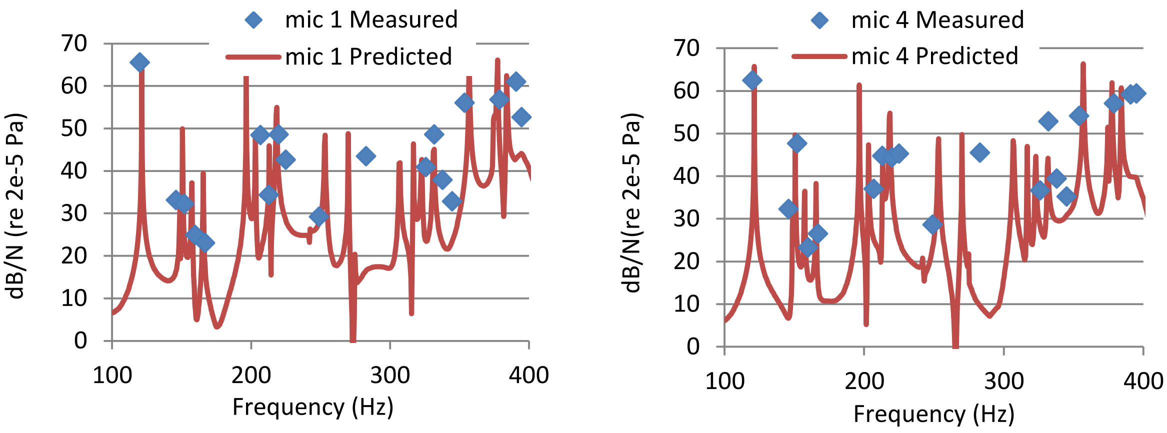
2. Detailed Modeling and Testing

The model with the structural FE coupled to the BEM fluid was exercised with the point excitation as shown in Fig. 6(a). Instead of using software recommended damping values in the initial investigation, in this session the damping values from a modal test of the structure were applied to the structural FE model. The obtained damping is very light and ranges from 0.03% to 0.2% damping loss factor. Due to the light damping the analysis was performed with a frequency spacing of 1/360th octave bandwidth. A frequency resolution ranges from a 0.2 Hz frequency step at 100 Hz to a 0.771 Hz frequency step at 400 Hz. Because test data was only available at observed peaks measured with a 1 Hz bandwidth, it is difficult to compare exactly what was measured. Also, the predicted resonances of the structure differ a bit (within 10%) from the measured frequencies [3]. When the structure damping is very small, a slight shift in the indicated natural frequency will result in a large difference in the acceleration and sound pressure level at a particular frequency. Therefore, one cannot compare amplitudes at a particular frequency; instead one has to look at nearby resonances to assess the relative correlation, which was an acceptable concept in the automotive industry [9]. Fig. 8 shows the comparison of the measured and predicted accelerations. The measured and predicted sound pressure levels at selected microphone locations, which are M1 and M4 shown in Fig 4, due to a unit force are compared in Fig. 9. Both the comparisons of the accelerations and sound pressure levels are up to 400 Hz, because only the testing data below 400 Hz are available. Comparisons are fairly good at most frequencies considering the difficulties with obtaining the test data.



(a) *(b)*

Figure 8: Measured data versus predictions of the acceleration of the cutting drum. (a) location on a vane, (b) location on the cylindrical region.



(a) *(b)*

Figure 9: Measured data versus predictions of the sound pressure radiated from the cutting drum. (a) microphone 1 (M1), (b) microphone 4 (M4).

4. CONCLUSIONS

This paper showed that numerical vibro-acoustic analysis is an effective tool to investigate the noise generation mechanisms of the longwall shearer drum. Four different analysis methods, including hybrid FE/SEA, FE, BEM, and FMM BEM, were compared for their capability of predicting sound radiation from a longwall cutting head, and the comparison indicates that the BEM results were the most accurate for this particular application. The hybrid FE/SEA results under-predicted the BEM results and it is mainly due to the fact that the hybrid method is mainly good for middle frequency range applications. It is also because that the geometry of the drum is not ideal for the hybrid method, which ignores the curvature and flattens the surface. The FE acoustic analysis did a better job than the hybrid method. However, because of some approximations with the radiation boundary condition made in the FE acoustic analysis, the FE results were consistently lower than the BEM results. Besides the advantage of the accuracy, the modeling of the BEM is also easier because only a surface mesh is needed, and in this case a shrink-wrapped mesh is a quick and straightforward approach. The BEM model can be easily converted to FMM BEM when the analysis goes to higher frequencies where the required mesh will be finer and the model size will increase. A validation test was conducted in the facility of a collaborating mine, and correlation between the coupled structural FE and the acoustic BEM model predictions and the experimental data from a cutting drum were reasonable. Improving the measurements may be made in the future in order to get better simulation-measurement correlation. So the BEM model was chosen as the best solution for further analysis of the longwall cutting drum sound radiation.

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