A COMPARISON OF BEAMFORMING PROCESSING TECHNIQUES FOR LOW FREQUENCY NOISE SOURCE IDENTIFICATION IN MINING EQUIPMENT

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ABSTRACT

In an effort to reduce Noise Induced Hearing Loss (NIHL) in the mining industry, the National Institute for Occupational Safety and Health (NIOSH) is conducting research to develop noise controls for mining equipment whose operators exceed the Permissible Exposure Level (PEL). The process involves three steps: 1) Noise source identification (NSI), 2) development of noise controls, and 3) evaluation of the developed noise controls. For the first and third steps, microphone phased array measurements are typically conducted and data are processed using the conventional beamforming (CB) algorithm. However, due to the size and complexity of the machines, this task is not straight forward. Furthermore, because of the low frequency range of interest, i.e., 200 Hz to 1000 Hz, results obtained using CB may show poor resolution issues which result in inaccuracy in the noise source location. To overcome this resolution issue, two alternative approaches are explored in this paper, namely the CLEAN-SC algorithm and a variarion of an adaptive beamforming algorithm known as Robust Capon Beamformer (RCB). These algorithms were used along with the CB algorithm to process data collected from a horizontal Vibrating Screen (VS) machine used in coal preparation plants. Results with the array in the overhead position showed that despite the use of a large array, i.e., 3.5-meter diameter, the acoustic maps obtained using CB showed "hot spots" that covered various components, i.e., the screen deck, the side walls, the I-beam, the eccentric mechanisms, and the electric motor. Thus, it was not possible to identify which component was the dominant contributor to the sound radiated by the machine. The acoustic maps obtained using the RCB algorithm showed smaller "hot" spots that in general covered only one or two components. Nevertheless, the most dramatic reduction in "hot" spot size was obtained using the CLEAN-SC algorithm. This algorithm yielded acoustic maps with small and well localized "hot" spots that pinpointed dominant noise sources. However, because the CLEAN-SC algorithm yields small and localized "hot" spots, extra care needs to be used when aligning the acoustic maps with the actual pictures of the machine. In conclusion, use of the RCB and the CLEAN-SC algorithms in the low frequency range of interest helped pinpoint dominant noise sources which otherwise would be very hard to identify.

INTRODUCTION

Despite several efforts to improve the working environment in the mining industry, noise is perhaps the most challenging hazard to overcome. For that reason, occupational NIHL continues to be the most prevalent illness among mine workers.

An analysis of audiograms for a large cohort of noise-exposed miners revealed that hearing impairment in this occupation increases exponentially with age. Consequently, 49% of metal/nonmetal miners and 90% of coal miners have hearing impairment by age 50, in contrast to only 10% of workers not exposed to occupational noise[1]. In this context, NIOSH is conducting research to reduce the sound radiated by mining equipment and thus minimize the exposure of miners to hazardous noise. The efforts of this research are geared towards the loudest machines along the entire production chain, i.e., from the extraction at the face to the coal preparation plants. As a result, several noise controls have been developed for underground and surface equipment[2-6].

With regard to coal preparation plants, a cross sectional survey conducted by NIOSH determined that the vibrating screen (VS) machines are among the loudest noise sources used in these facilities, responsible for the worker noise exposures[7]. Furthermore, the study revealed that 43.5% of coal preparation plant employees are exposed to noise levels that exceed the PEL[8]. Analysis of the data reported to the Mine Safety and Health Administration (MSHA) by the mining industry showed that there are currently 421 coal preparation plants in production in the United States.

The first step in the development of engineering noise controls involves the noise source identification (NSI) process, which consists of identifying the spatial location and the frequency content of the dominant noise sources. In the second step, appropriate (adequate) noise controls are developed. Then, the performance of these noise controls is determined by laboratory tests. Finally, the effectiveness of the controls in reducing the operator's noise exposure is attained *in situ*.

The first and third steps of the noise control development are achieved using microphone phased arrays. Usually, phased array data is processed using a CB algorithm which renders acoustic maps at each frequency of interest.

Due to the massive nature of mining equipment, these machines are built using large and thick steel panels and thus radiate noise mostly at low frequencies, i.e., 200 Hz to 1000 Hz. The challenge of using phased arrays for mining applications is then related to the frequency range of interest and the resolution obtained at such frequencies.

There are two alternatives to overcome the low resolution issue. The first alternative consists of increasing the array aperture, i.e., the size of the array. However, there are several physical constraints that limit this alternative such as the dimensions and shape of the machines, and the distance from the array to the device under test. The second alternative consists of using advanced beamforming algorithms that improve the resolution of the acoustic maps at low frequencies.

Previous work on noise source identification on a vibrating screen involved the use of two different arrays: A 1.98-meter diameter array provided with 49 microphones, and a 3.5-meter diameter array equipped with 121 microphones. When the latter array was used, the resolution of the acoustic maps in the 200 Hz – 1000 Hz frequency range was improved by approximately 50%. However, at some frequencies, it was still not clear which components were responsible for most of the sound being radiated.

This paper explores two advanced beamforming tools to improve the resolution of the acoustic maps at low frequencies: the Robust Capon Beamformer (RCB) and the CLEAN-SC algorithm.

NOMENCLATURE

$b\left(\vec{x}_b\right)$ is the beamforming output.

$\vec{C}\left(\vec{x}\right)$ is the array propagation vector for a point at $\vec{x}$

$\mathbf{G}$ is the cross-spectral matrix of the microphone signals.

$\vec{r}_j$ is the distance from point $\vec{x}_b$ to microphone *j*.

$\vec{w}(\vec{x}_b)$ is the microphone weight vector.

$\vec{x}_b$ is the position of a point in the sound field.

$\vec{x}_j$ is the position of microphone *j*.

CONVENTIONAL BEAMFORMING

Conventional beamforming is based on the delay-and-sum concept. In this approach, the signal of each microphone in the array is delayed by the propagation time from a point in space. The signals are then added to obtain the resulting noise. If a source is present, the signals add constructively and a large output is obtained. If not, the signals add destructively and thus yielding a smaller output. Since the location of the source is not known a priori, a set of scanning points must be tested to determine if a source is present.

For stationary sources it is common to work in the frequency domain[9] where a time delay is equivalent to a phase shift and conventional beamforming takes the following form[10],

$$b\left(\vec{x}_b\right) = \vec{w}^*(\vec{x}_b)\,\mathbf{G}\,w(\vec{x}_b) \tag{1}$$

In equation (1), the weight vectors $w(x_b)$ are used to "steer" the array towards x_b and obtain the beamforming output $b(x_b)$, representing the sum over the array microphones of the acoustic pressure induced by the source located at x_b. The weight vectors are usually defined using the array propagation vector as,

$$\vec{w}\left(\vec{x}_b\right) = \frac{\vec{C}\left(\vec{x}_b\right)}{\left\|\vec{C}\left(\vec{x}_b\right)\right\|} \tag{2}$$

where the components of the propagation vector $\vec{C}\left(\vec{x}_b\right)$ are the free-space Green's function given by,

$$C_j\left(\vec{x}_b\right) = \frac{e^{-ik\left|\vec{x}_b - \vec{x}_j\right|}}{4\pi\left|\vec{x}_b - \vec{x}_j\right|} = \frac{e^{-ikr_j}}{4\pi r_j} \quad (3)$$

Ideally, if a point source exists at $\vec{x}_b$, the beamforming output would be the mean squared value of the pressure at the array due to such source and it would be zero if there is not a source at $\vec{x}_b$. However, the fact that there is a finite number of microphones in the array results in the presence of sidelobes (i.e. lobes not associated to actual sources) in the acoustic maps. The resolution of the array at a particular frequency is defined as the size of the region for which the levels are within 3 dB of the peak value in the mainlobe. For conventional beamforming, the resolution is directly proportional to the wavelength.

ROBUST CAPON BEAMFORMING

This technique is a variation of the Capon beamformer[11] that accounts for uncertainties in the steering vector by using an ellipsoidal uncertainty set. Different implementations of the approach were developed by Li, Stoica and Wang[12-14]. This approach falls in the category of diagonal loading. Diagonal loading also improves robustness. This approach is data-adaptive, i.e. the algorithm uses the data to improve the results, making it less sensitive to errors in the steering vector.

As a result, array resolution and signal-to-noise ratio are improved. The Robust Capon Beamformer approach has also been shown to be more computationally efficient than other Capon beamformers[12].

CLEAN-SC

This method developed by Sijtsma is based on the CLEAN algorithm used for astronomy developed by Högbom[15]. Sijtsma's work extends CLEAN to account for spatial source coherence[16]. This iterative approach basically removes the contribution of sources that are spatially coherent with a major source. This is accomplished by taking advantage of the fact that sources are spatially coherent with their corresponding sidelobes.

The iteration goes as follows: 1) remove the highest source in the map (and its spatially correlated sidelobes) from the cross spectral matrix, 2) remove the part of the map associated with the source removed, i.e., its point spread function, and 3) add the source to a new "clean" map. This process is repeated until the energy in the cross-spectral matrix is similar to the energy of the last source removed.

As a result, the new map only shows the actual noise sources and not their sidelobes. Since the approach uses a single point in the grid as the source location, the new map is created using a user defined array resolution, i.e. a beam of an arbitrary diameter in which the source level drops 3 dB from its center.

EXPERIMENTAL SETUP

Phased array measurements were conducted in the Hemi-anechoic chamber of the PRL. This chamber is 16.8-meter long by 10.1-meter wide, by 6.4-meter high. The walls and ceiling are treated with acoustic absorptive material, i.e. fiberglass, resulting in a chamber cut-off frequency of 100 Hz according to ISO 3744[17].

The device under test was a horizontal dewatering VS machine used in coal preparation plants. The VS machine consists of a boxed structure that is suspended on coil springs. Figure 1 shows a schematic of the VS machine and the phased array in the Hemi-anechoic chamber.

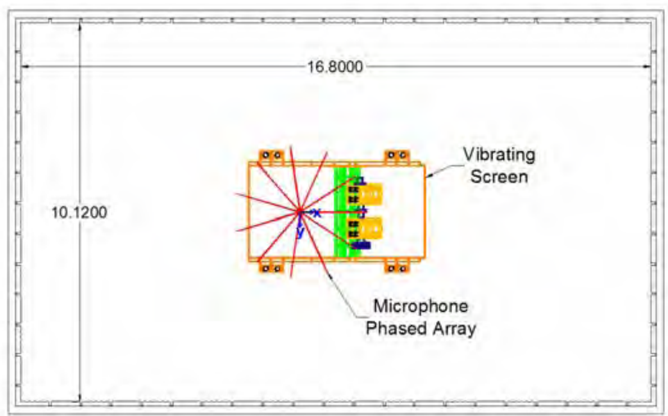


Figure 1. Schematic of the VS and the phased array in the Hemi-anechoic chamber.

The VS machine is driven by two eccentric mechanisms that set the structure into vibration at a 45-degree angle with respect to the vertical axis (z-axis).

The excitation for the noise radiated by the screen body is mainly provided by the eccentric mechanisms and the gears used to drive them. Each eccentric mechanism uses two rotating unbalanced shafts. One shaft of the first eccentric mechanism is driven by an electric motor via a belt/pulley system. This shaft is directly coupled to one of the shafts in the second eccentric mechanism. The second shaft in each eccentric mechanism is driven by the main shaft through a gear set. Figure 2 displays a top view of the VS machine where all the various components are shown.

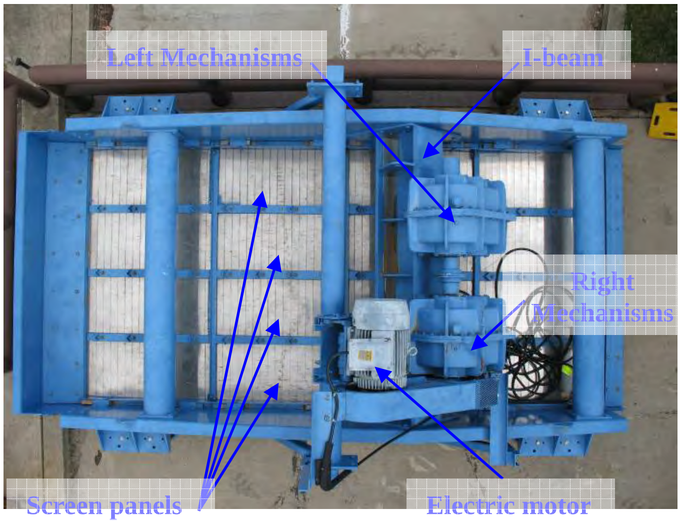


Figure 2. VS machine as seen from the top.

A 121-channel, 3.5-m diameter microphone phased array designed and built by AVEC, Inc. was used for this series of measurements. This array is an 11-arm star array with a proprietary microphone arrangement. In order to provide the most complete data set for noise source identification, the array was mounted to a movable truss, i.e., gantry crane, at the NIOSH facility. It was mounted in two configurations: vertical (microphone plane parallel to the walls) and horizontal (microphone plane parallel to the ground). Figure 3 shows the VS machine in the hemi-anechoic chamber with the array in the overhead (horizontal) position.

Figure 3. VS machine in the Hemi-anechoic chamber at PRL with the AVEC phased array in the overhead position.

Data was collected with the array centered at three different places above the vibrating screen (horizontal configuration), and then from each side of the machine (vertical configuration). This paper includes results for the array centered on top of the vibrating screen.

The data acquisition system that was used for these measurements is a 128-channel simultaneous acquisition system with signal conditioning and anti-aliasing filtering also built by AVEC. The sampling frequency used was 51.2 kHz. For each configuration, 16 seconds of continuous data were collected. Processing was performed in 1/3rd octave bands. Conventional beamforming results were obtained using AVEC's phased array software. Results for CLEAN-SC and RCB were obtained with non-commercial implementations of such algorithms developed by AVEC for research purposes.

RESULTS

As shown in figures 4 through 6, there are significant differences in the acoustic maps. Note that the location of the sources obtained with CLEAN-SC agrees to those found using CB. This is related to the procedure to find noise sources. Thus, the maximum source on each map is "removed" from the cross-spectral matrix and a source with such level is located on the "clean" map. As explained before, this process is repeated until the energy in the cross spectral matrix is less than the energy "recovered" for the last source. Keep in mind that in this approach, the resolution is arbitrarily set by the user, and hence the extraordinary resolution of the technique. It was precisely this extraordinary resolution on the acoustic maps that allowed pinpointing dominant noise sources on the various components of the VS machine. The fact that in some cases sources that are not well defined (i.e. not circles) are "condensed" to a single point is due to the ability of CLEAN-SC to remove all the power from the cross-spectral matrix that is correlated with the source identified in each step. The map resulting after extracting all the major noise sources has not been plotted in these figures since we were only interested in the major noise sources.

However, the fact that some noise sources are "condensed" to a single point requires that extra care should be practiced when aligning the acoustic map with the picture of the device under test, i.e. the VS machine in this case. Consider for instance Figure 5c that shows a dominant noise source in the left eccentric mechanism. If the picture is not properly aligned, i.e. suppose the picture is off to the left by a couple of inches, then the results would indicate that the noise source is located in the I-beam. This would lead to an erroneous NSI process.

At low frequencies, RCB improves the resolution allowing for more accurate noise source identification. However, note that results obtained with RCB show that some of the sources "disappear", especially at higher frequencies, as is the case when comparing figure 6a and 6b. This suggests that some of the sources in the CB maps are actually sidelobes.

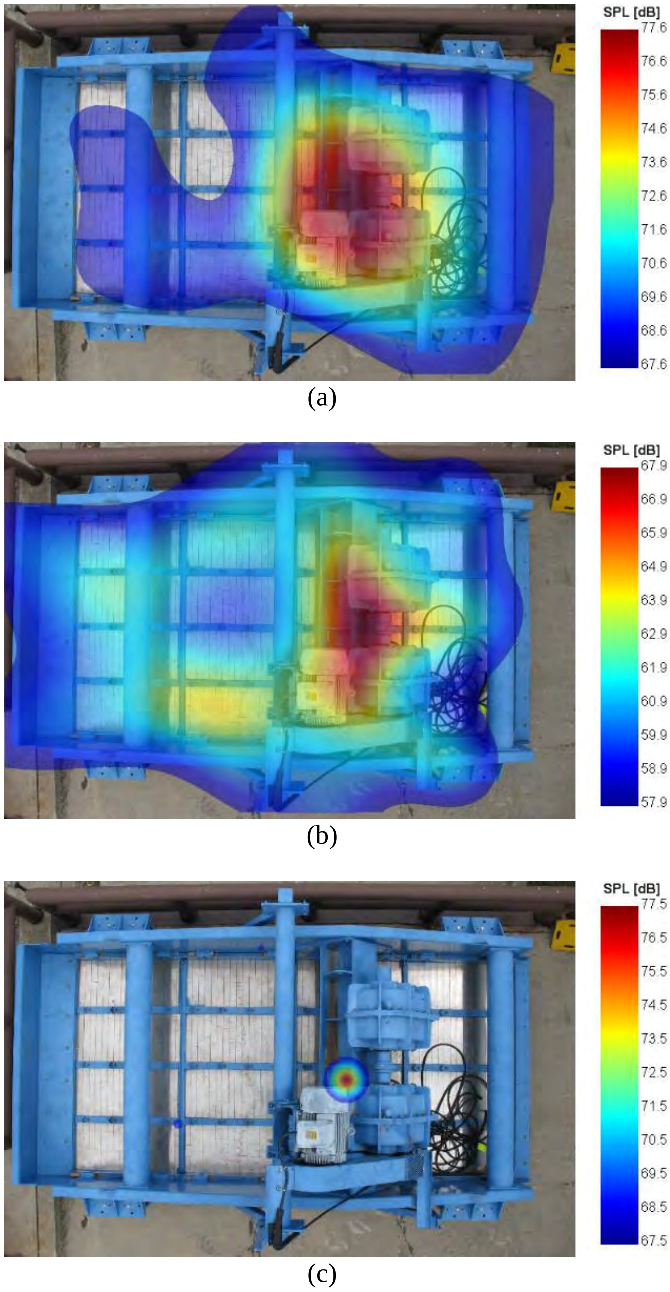


Figure 4. Comparison of acoustic maps at 250 Hz obtained with: a) CB, b) RCB, and c) CLEAN-SC.

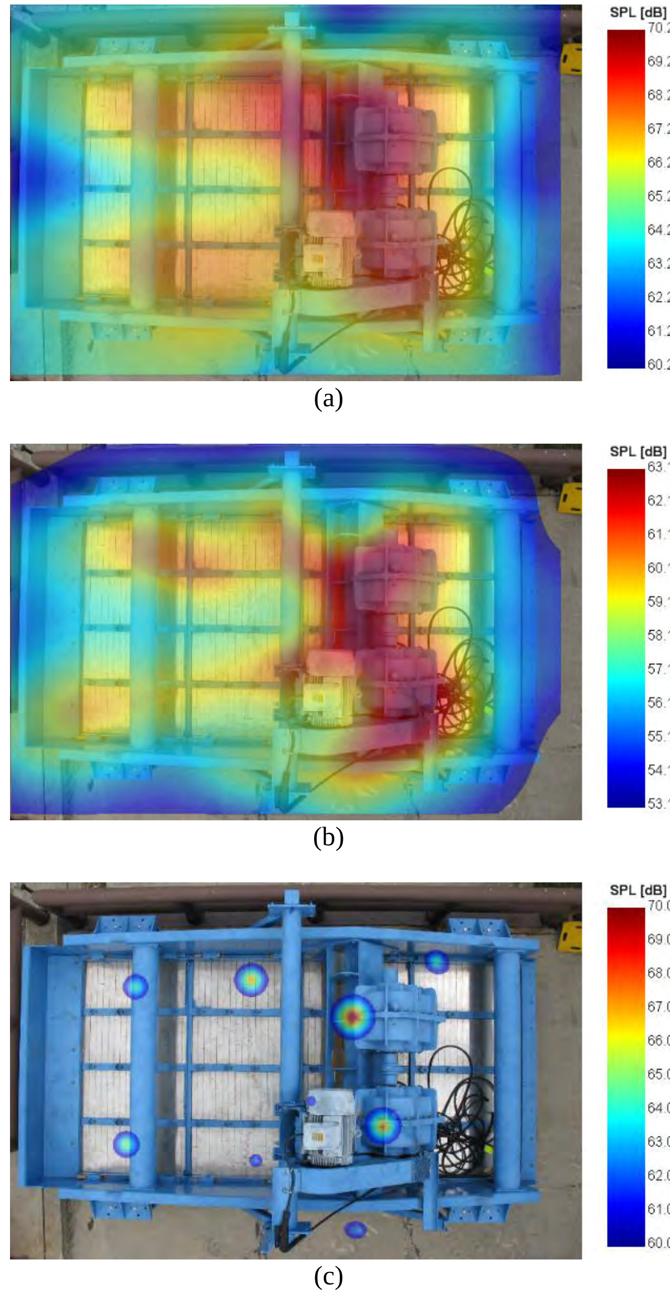
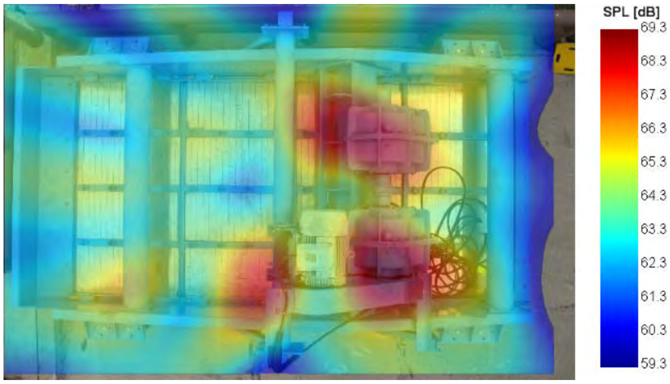


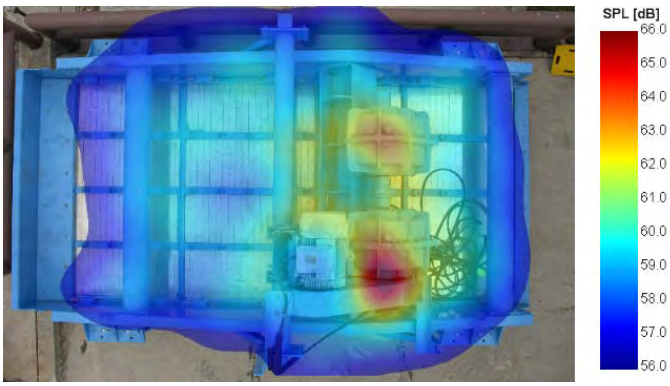
Figure 5. Comparison of acoustic maps at 315 Hz obtained with: a) CB, b) RCB, and c) CLEAN-SC.

These results are confirmed by analyzing the CLEAN-SC results, in which some of the hot spots relative levels have changed dramatically, i.e., the hot spots are coherent with each other and hence removed by CLEAN-SC when the corresponding main source is subtracted from the map (see Figure 6).

It should be noted that for this effort, a parametric study of the effect of the parameter (ε) on the RCB results was not conducted. This parameter is user defined and it describes the uncertainty in the steering vector. A conservative approach was used by applying the parameter value ε=2 suggested in the literature[14].



(a)



(b)

(c)

Figure 6. Comparison of acoustic maps at 400 Hz obtained with: a) CB, b) RCB, and c) CLEAN-SC.

CONCLUSION

The implementation of an adaptive beamforming algorithm (RCB) and a post-processing technique (CLEAN-SC) on the results obtained from a VS machine using a 3.5-meter array were studied as a mean to improve the resolution and thus the accuracy of the NSI process at low frequencies, i.e., from 200 Hz to 1000 Hz. Both methods have shown significant improvements when compared to the results obtained using conventional beamforming in this frequency range. Furthermore, it was the use of these tools that allowed precise and rapid pinpointing of dominant noise sources on the various components of the VS machine. An alternative approach such as intensity mapping would be inpractical due to the dimensions and complexity of the machine.

The results obtained at PRL with both the RCB and the CLEAN-SC methods will be used to develop noise controls to attenuate the sound radiated by the VS machine, and thus achieve the ultimate goal of reducing the noise exposure of coal preparation plant employees.

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