Application of a microphone phased array to identify noise sources on a horizontal vibrating screen

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ABSTRACT

In coal preparation plants, workers are often exposed to sound levels exceeding 90 dB(A). Vibrating screens are viewed as a significant contributor to preparation plant noise. Reducing the sound levels generated by vibrating screens could reduce the noise exposures of preparation plant employees. The National Institute for Occupational Safety and Health (NIOSH) measured the sound power level generated by a horizontal vibrating screen with the screen either directly on the floor or on rubber isolation pads. The sound power level was 100.6 dB(A) with the screen directly on the floor. With the screen placed on isolation pads, the sound power level was 100.6 dB(A) without the belt guard rattling and 108.3 dB(A) with the belt guard rattling. The 160 Hz to 800 Hz frequency range was dominant when the belt guard was not rattling whereas the 1 to 10 kHz frequency range was most significant when the belt guard was rattling. A microphone phased array was used to examine noise sources on the screen. The belt guard, eccentric mechanisms, and steel coil springs were found to be significant noise sources. This paper will provide detailed information on the findings of the research.

1. INTRODUCTION

In 1996, NIOSH published the National Occupational Research Agenda, which identified hearing loss as the most common job-related disease in the United States.[1] Approximately 30 million workers are exposed to hazardous sound levels alone or to hazardous sound levels in conjunction with ototoxic agents.[2] Despite more than 30 years of noise regulation in the mining industry, mine workers develop hearing loss at a significantly higher rate compared to the non-noise exposed population. An analysis of audiograms conducted by NIOSH in 1996 shows that by the age of 50, nearly 90% of coal miners had a hearing impairment.[3] In contrast, only 10% of those who are not exposed to occupational noise experienced a hearing loss by the same age.

The Mine Safety and Health Administration (MSHA) modified its rules regarding noise exposure in 1999 in an effort to reduce the occurrence of noise-induced hearing loss.[4] Rather

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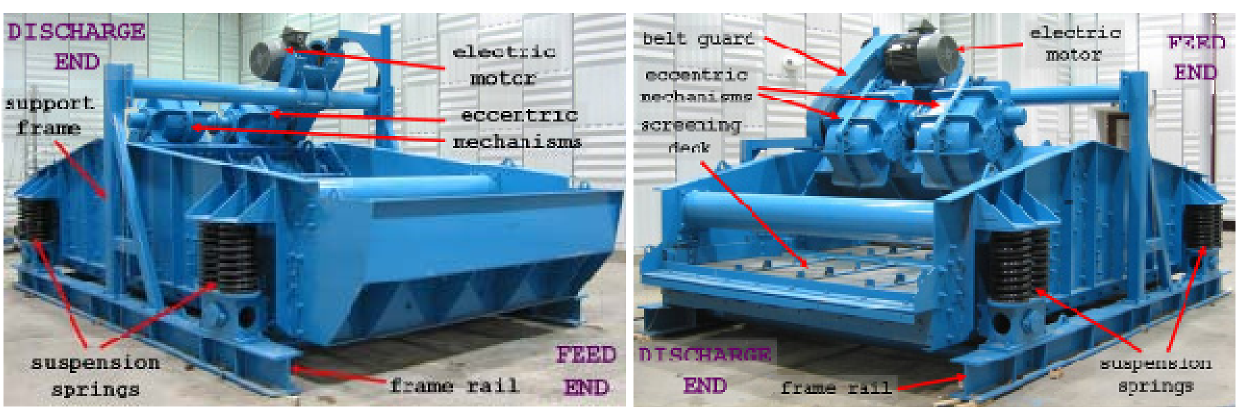
than relying solely on hearing protection devices, MSHA's new rule requires mine operators to use all feasible engineering and/or administrative controls to reduce the noise exposures of overexposed miners'. However, for many machines, such as vibrating screens, noise controls that reduce the operator's noise exposure below the MSHA Permissible Exposure Level (PEL) are not currently available.

In 2000, there were 212 preparation plants in operation in the US and 129 of these plants were located in three states: Kentucky, Pennsylvania, and West Virginia.[5] NIOSH studies have shown that workers who spend a significant portion of their shift working in a coal preparation plant can experience noise exposures which exceed the MSHA PEL for noise. NIOSH data show that 20 out of 46 coal preparation plant workers had noise exposures that exceeded the MSHA PEL noise dose.[6] MSHA PEL noise doses up to 220% have been recorded for preparation plant workers in jobs with titles such as stationary equipment operator, froth cell operator, plant operator, plant controls man, third floor operator, wet plant attendant, sump floor operator, plant backup, and plant mechanic. These job classifications require the worker to spend a significant portion of a shift in the plant while working around slurry pumps, dryers, centrifuges, and vibrating screens.

A horizontal vibrating screen (see Figure 1) is a large machine used to process clean coal that has been separated from refuse materials using a water-magnetite mixture. This magnetite is recovered because the magnetite lowers the heating value of coal and it can be re-used in the processing plant. The screen body has four sides made of steel plates with a bottom screening surface made of steel wire welded to a frame with small gaps between the wires. The body of the screen is supported on a steel coil spring suspension. One or more vibration mechanisms are mounted to a steel beam that spans the width of the screen. These vibration mechanisms, which use rotating eccentric shafts to generate vibration, are belt-driven using an electric motor. The screen is designed such that it vibrates on roughly a 45 degree angle. Coal flows into the feed end of the screen from a delivery chute. As the screen vibrates, the material moves along the deck and under a water spray that rinses the magnetite from the coal. The liquid and fine coal particles pass through the gaps in the screening deck as the material flows toward the discharge end of the screen. Finally, the rinsed coal falls off the discharge end of the chute to continue with further processing.



(a) (b)

Figure 1: A horizontal vibrating screen used to process coal viewed from (a) feed end and (b) discharge end.

Since they are used to size, separate, and dewater both coal and refuse (rock) of various sizes, screens may be located on many floors within a preparation plant. The number of screens in a processing plant can range from a single screen to more than a dozen. Consequently, preparation plant workers can be exposed to high sound levels generated by screens multiple times during a shift as they move and work throughout the plant. Vibrating screens are a major noise problem in most coal preparation plants because screens are used extensively in the plants, are usually located in high traffic areas, and can generate high noise levels.[7]

NIOSH performed sound level measurements near a group of eight horizontal vibrating screens used to process clean coal.[8] These measurements indicated that the sound levels ranged from 94 to 98 dB(A) with the plant processing coal (see Figure 2). With the coal flow turned off and the screen vibration mechanisms turned on, the sound levels ranged from 89 to 97 dB(A). The sound levels decreased significantly with increasing distance from the screens, indicating that the screens dominate the overall A-weighted sound level in this area of the preparation plant. In order to reduce the potential for overexposing preparation plant workers to noise, noise controls must be developed to address dominant noise sources on the screen. However, first these noise sources must be identified.

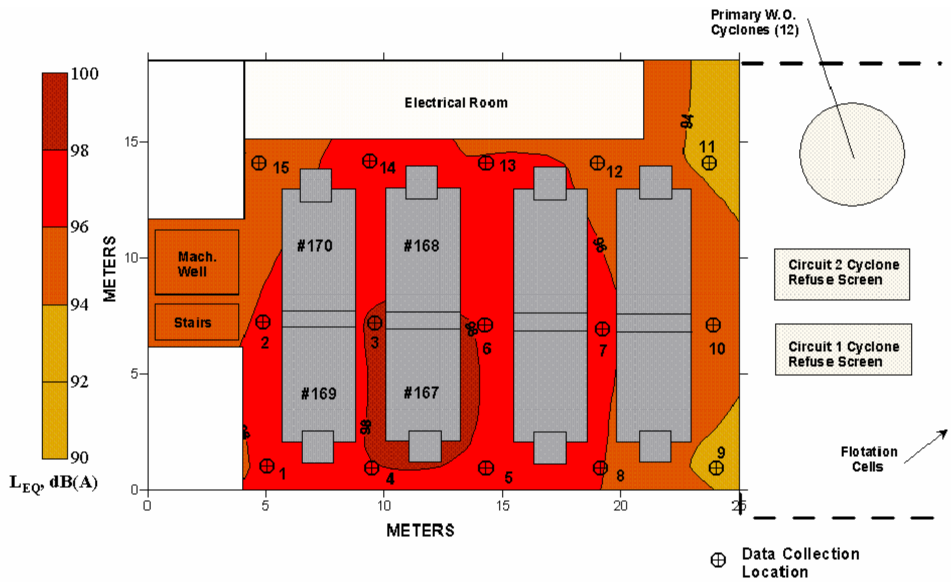


Figure 2: Sound levels measured around a group of 8 horizontal vibrating screens while processing coal.

2. TEST SETUP AND INSTRUMENTATION

All testing was performed using a dual-vibration mechanism Conn-Weld G-master horizontal vibrating screen with a 2.44 m x 4.88 m screening deck. The A-weighted sound power level of the vibrating screen was measured in the NIOSH Pittsburgh Research Laboratory (PRL) reverberation chamber (see Figure 3) which is NVLAP accredited for sound power level measurements. The sound power levels were determined in one-third-octave bands with the screen placed directly on the reverberation chamber floor and with the screen supported on vibration-isolation pads[9]to prevent vibration-radiated noise from the reverberation chamber floor as recommended by ISO 37xx. For the data collected with the screen directly on the chamber floor, wooden wedges were driven under the frame rails to prevent the screen from rocking on the floor. A Bruel & Kjaer Pulse data acquisition system and 18 Bruel & Kjaer Type 4188 microphones were used to measure the sound pressures. First, the sound pressure levels were measured using a Bruel & Kjaer Type 4204 Reference Sound Source. Next, the sound pressure levels were measured with the vibrating screen turned on. A measurement time of 30 seconds was used for all tests. The operating speed of the eccentric mechanisms was checked periodically throughout the tests with a tachometer. From the measured sound pressure levels, the sound power levels were calculated by

$$L_{w,DUT} = L_{w,RSS} - \left(L_{p,RSS} - L_{p,DUT}\right) \qquad (1)$$

where $L_{P,RSS}$ is the spatially-averaged sound pressure level inside the reverberation chamber for the reference sound source, $L_{P,DUT}$ is the spatially-averaged sound pressure level inside the reverberation chamber for the vibrating screen, $L_{W,RSS}$ is the calibrated sound power level of the reference sound source, and $L_{W,DUT}$ is the calculated sound power level of the vibrating screen.

(a) (b)

Figure 3: Horizontal screen in reverberation chamber for sound power level measurements with the screen (a) placed directly on the floor and (b) with the screen supported with vibration isolation pads.

Noise source identification was performed using the beamforming technique.[9] The screen was positioned in the NIOSH PRL hemi-anechoic chamber with the screen directly on the chamber floor with wooden wedges driven under the frame rails to prevent rocking. To collect the beamforming data, a Pulse data acquisition system was used to simultaneously record the sound pressures from a 42-microphone wheel array (see Figure 4).

(a) (b)

Figure 4: (a) Vibrating screen in hemi-anechoic chamber (b)View of vibrating screen from beamforming array.

Measurements were performed at a distance of 5.54 meters from the sides of the screen and 3.05 meters from the ends of the screen, so the entire screen would fit within the measurement area of the array. Measurements were also performed with the array a distance of 2.3 meters from the screen with multiple measurements along the ends and sides to examine noise sources with better spatial resolution. The data from the array was post-processed using Bruel & Kjaer's Beamforming application using free-field processing and pressure scaling. First, calculations were performed with synthesized one-third-octave bands to reduce the analysis time. Next, calculations were performed with the results synthesized in 16 to 32 Hz bands so the results could be analyzed in more detail. In each case a calculation grid spacing of 0.050 m was used.

3. TEST RESULTS AND DISCUSSION

Figure 5 shows the A-weighted sound power level of the vibrating screen in 1/3-octave bands. With the screen directly on the reverberation chamber floor with wooden wedges under the frame rails the overall A-weighted sound power level was 100.6 dB. The figure shows that the 160 through 800 Hz 1/3-octave bands dominate the spectrum. In addition, the spectrum exhibits a secondary hump in the 1 kHz through 3.15 kHz 1/3-octave bands. These results are similar to those measured in an operating preparation plant.[8]

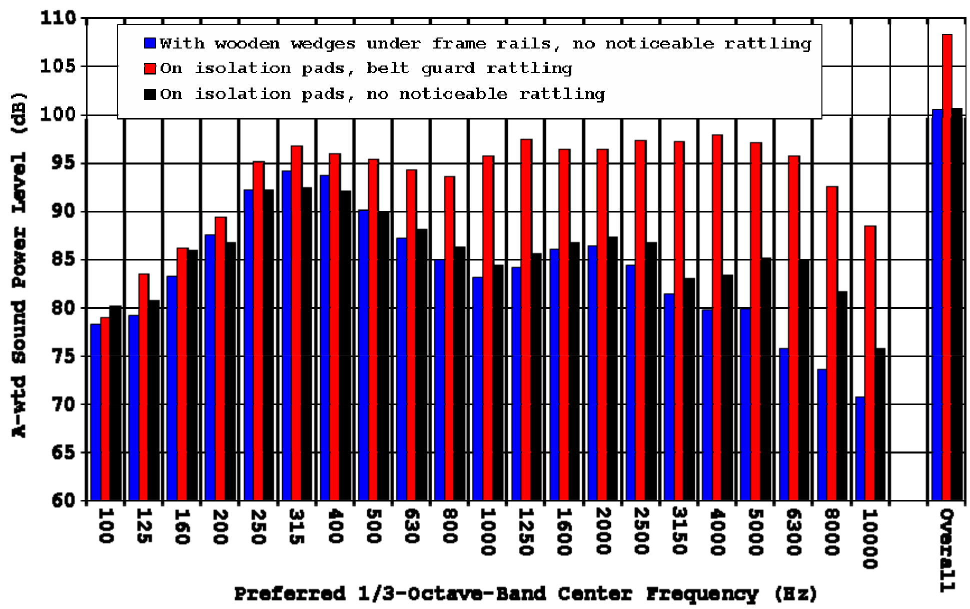


Figure 5: A-weighted sound power level of the vibrating screen in 1/3-octave bands.

Next, the screen was tested with the frame rails resting on a set of vibration isolation pads that were designed to isolate vibrations above 10 Hz. Ironically, placing the screen on vibration isolation pads increased the A-weighted sound power level to 108.3 dB. The most significant increases occurred at the higher frequencies. After observing the operation of the screen, it was noticed that the belt guard was rattling against the mechanism support. Further inspection revealed that the structure used to support the front belt guard appeared to be vibrating more. This may be due to the decrease in frame rail stiffness due to different boundary conditions with the frame rails supported along their length versus using a soft suspension.

Another set of measurements was performed with a force applied to the belt guard support to prevent it from rattling. In this case, the overall A-weighted sound power level decreased back to the original value of 100.6 dB. However, although belt guard rattling was not observed, the 2 through 10 kHz 1/3-octave bands show significant increases. Since the lower frequencies dominate the spectra, these increases did not impact the overall A-weighted sound power level. Once again, the 160 through 800 Hz 1/3-octave bands dominate the spectrum and the 1 kHz through 3.15 kHz 1/3-octave bands exhibit a secondary hump.

Since preventing the belt guard from rattling is easily accomplished by increasing the clearance between the belt guard and the mechanism support, it is more important to focus on the data without a rattling belt guard. Therefore, the results with the screen directly on the reverberation chamber floor were examined in further detail. Figure 6 shows the percentage contribution of the 100 Hz through 10 kHz 1/3-octave bands to the overall A-weighted sound power level. The figure clearly shows the dominance of the 160 Hz through 800 Hz 1/3-octave bands. These bands account for about 82% of the overall A-weighted sound power level. Adding up the in-band sound power levels for these bands show they account for 99.7 dB of the 100.6 dB overall A-weighted sound power level. The 1 kHz through 5 kHz 1/3-octave bands account for about 16% of the overall A-weighted sound power level. Summing the in-band levels across this frequency range shows they account for 92.7 of the 100.6 dB overall A-weighted sound power level.

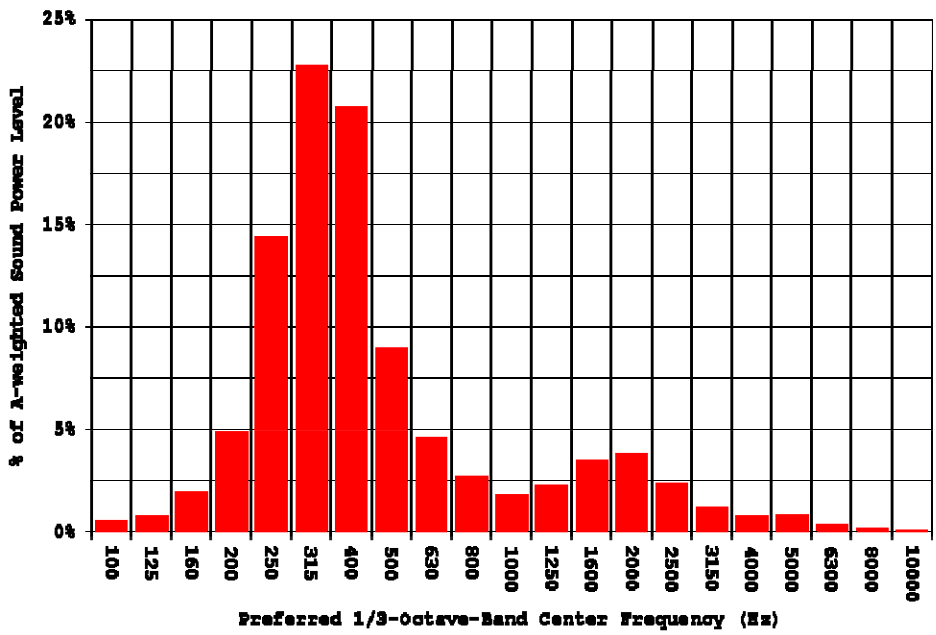
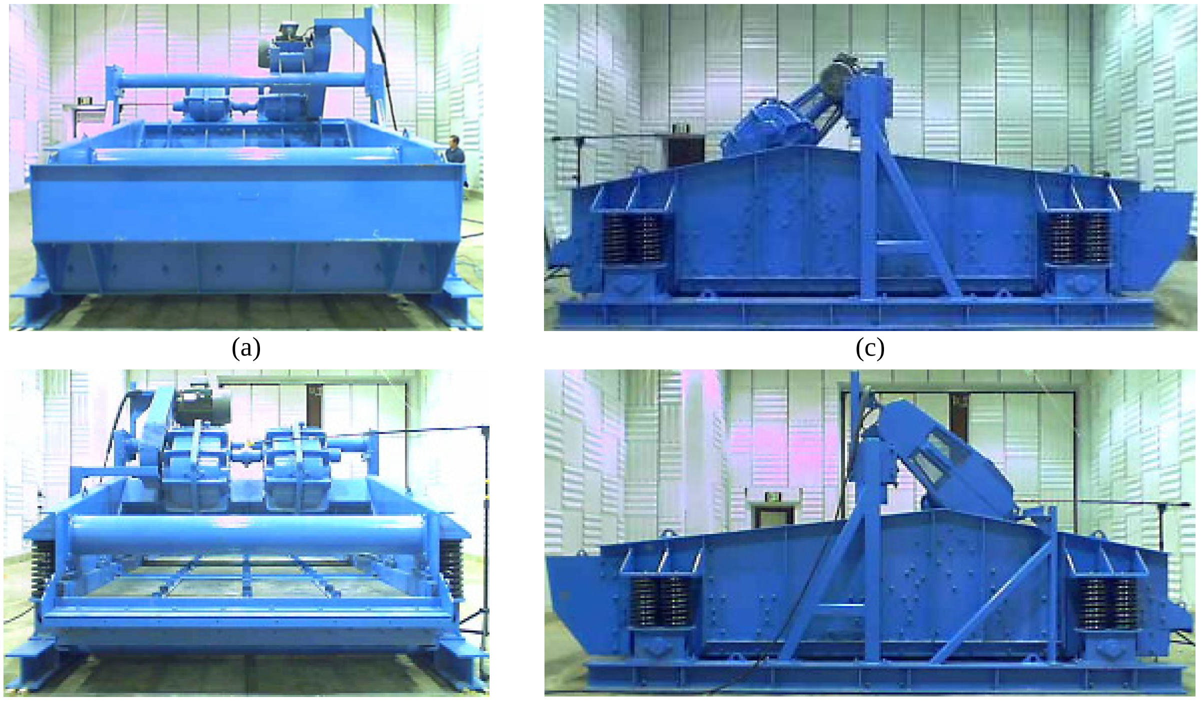


Figure 6: Percent contribution of each 1/3-octave-band to the overall A-weighted sound power level measured with the screen directly on the reverberation chamber floor.

The goal of the NIOSH vibrating screen project is to reduce the overall A-weighted sound power level by 10 dB. Noise sources in both frequency ranges, 100 Hz through 800 Hz and 1 kHz through 5 kHz, must be addressed to accomplish this goal. Due to the limited spatial resolution of the NIOSH beamforming array at frequencies below 1 kHz, the work discussed in this paper focuses on the beamforming results above 1 kHz. To identify noise sources below 1 kHz, a second series of beamforming measurements has been performed with a much larger array that provides acceptable resolution down to about 200 Hz. These results will be published in the future. It must be understood that addressing only one of these frequency ranges will not accomplish the project goal.

Figure 7 shows the feed end, discharge end, left side, and right side of the screen. These images are taken directly from the camera positioned at the center of the beamforming array from the measurements performed at sufficient distance to view the entire end or side. These images are presented to enable the reader to examine the screen without the overlaid contours of the beamforming results. The beamforming results for the full screen measurements for the 1 kHz through 5 kHz frequency bands will be discussed below. All contours are displayed with pressure scaling. The values are determined by the software at the calculation plane using a plane wave approximation of the sound field in the calculation plane. It is important to note that belt guard rattling was not noticed when the data was collected.



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

Figure 7: Screen images from the center of the array: (a) feed end,(b) discharge end, (c) left side, and (d) right side.

The beamforming results for the 1 kHz 1/3-octave band are shown in Figure 8. Recall the array was positioned 3.05 meters from the ends of the screen and 5.54 meters from the sides of the screen when performing the measurements. These are the respective values what were used for the source distance in the calculation plane. Due to the depth of the vibration mechanisms and other noise sources, each view must be examined to identify the location of noise sources. From the views from the feed end, left side, and right side, the dominant source for this band appears to be either the right mechanism or the belt guard. Examination of the view from the discharge end also shows the belt guard and right vibration mechanism to be potential noise sources. However, two other apparent sources are shown below the cross-tube. Inspection of the narrowband results was used to determine if these sources are real sources, reflections from the floor, or ghost images produced from side lobes that are summed across a large frequency band.

Figure 9 shows the narrowband beamforming results for the 928 Hz through 1.02 kHz frequency range. Each individual frequency band was examined prior to summing the results across this range and to ensure each showed similar source locations. The view from the discharge end shows the belt guard as the primary noise source. Below the cross-tube, two apparent sources are also visible. The side views show areas of high noise radiation near the middle of the screen near the bottom. These are the sources that are shown below the cross-tube in the view from the discharge end.

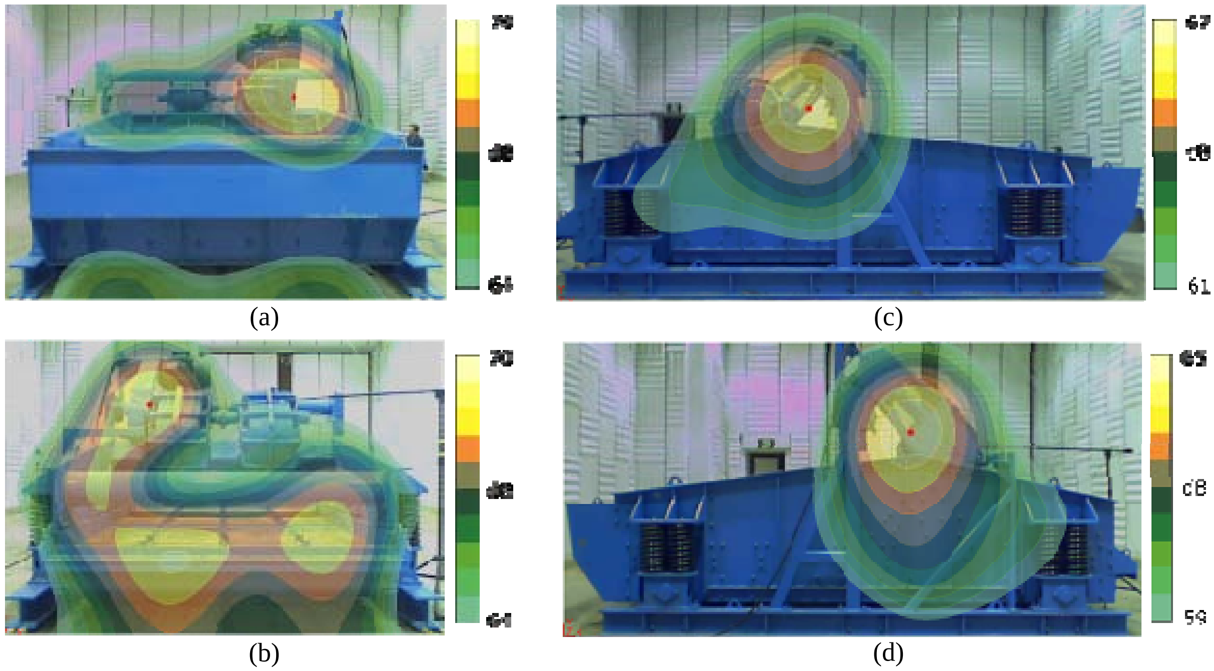


Figure 8: Results for the 1 kHz 1/3-octave band - (a) feed end (b) discharge end (c) left side and (d) right side.

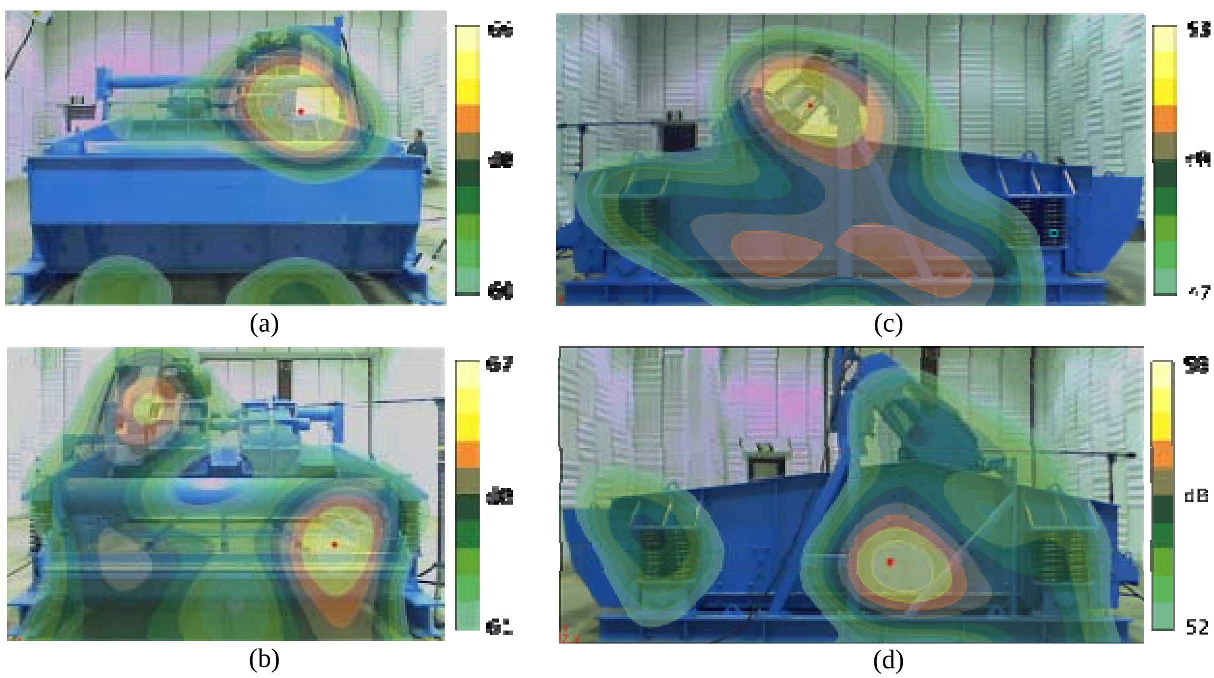


Figure 9: Narrowband results for 928 Hz - 1.02 kHz - (a) feed end (b) discharge end (c) left side and (d) right side.

It is important to note that the right view appears to show the springs to be a source of noise. The screen is designed to have a spring-within-a-spring design at each mounting location. On the feed end, there is one large coil spring and a large coil spring with a smaller inner spring on each side. On the discharge end, there are two sets of inner and outer springs. It is possible that the inner and outer springs rattle against one another during screen operation.

The beamforming results for the 1.07 through 1.12 kHz frequency range are shown in Figure 10. The view from the feed end appears to indicate two sources near the front of the screen. The view from the discharge end of the screen shows the right mechanism and belt guard as sources. In addition, there appears to be a source to the left and right edges of the cross-tube. The left side view shows the springs and the eccentric mechanisms to be sources. Finally, the right side shows the belt guard or mechanisms and a spot on the frame just behind the discharge end coil springs.

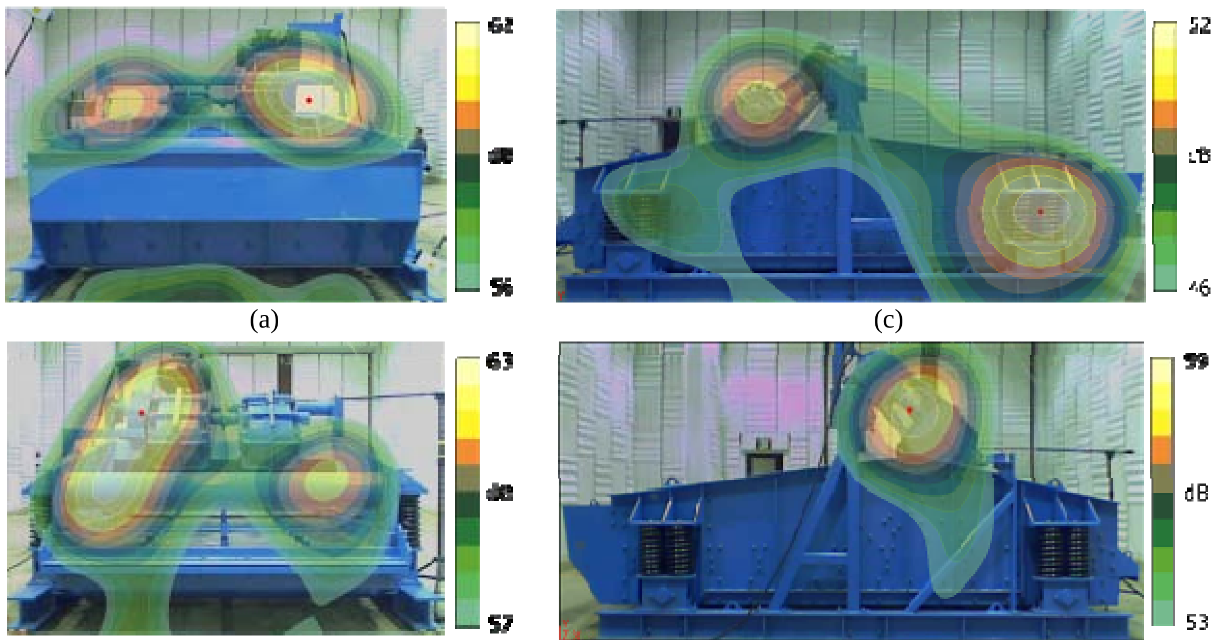


Figure 10: Narrowband results for 1.07 - 1.12 kHz - (a) feed end (b) discharge end (c) left side and (d) right side.

The information from all the views must be scrutinized to understand what each image shows. The apparent source on the left side at the discharge end is due to the coil springs. Since the calculation plane is at the surface of the screen closest to the array, the positions of sources at the opposite end of the screen are skewed. The two sources near the cross-tube on the view from the discharge end of the screen are probably due to the coil springs on the left side and the spot on the frame just behind coil springs on the right side. Using all the information, the important sources for this frequency range are the right vibration mechanism, belt guard, and feed end coil springs.

Figure 11 shows the beamforming results for the 1.25 kHz 1/3-octave band. In each view, the area around the right vibration mechanism, belt guard, and electric motor seems to be dominant. The results for the left side show the area above the coil springs as a possible source. The narrowband results were examined to get a better understanding of the sources in this band.

The narrowband results summed from 1.14 to 1.2 kHz are shown in Figure 12 for the discharge end and left side views. The discharge end view shows a source on the belt guard and a source near the cross-tube along the left side of the screen. The left side view shows sources near the eccentric mechanisms and/or belt guard and from the area above the feed end coil springs. Combining all the information, the source that appears near the cross-tube is really the source near the coil springs on the feed end of the machine.

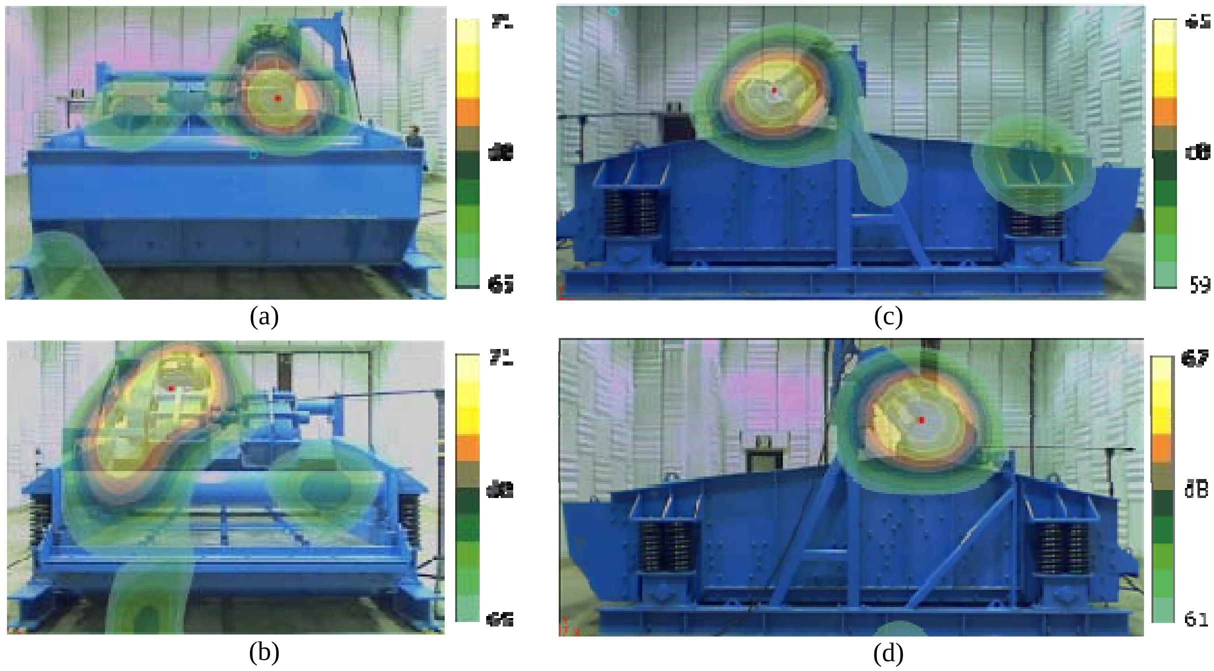


Figure 11: Results for the 1.25 kHz 1/3-octave band - (a) feed end (b) discharge end (c) left side and (d) right side.

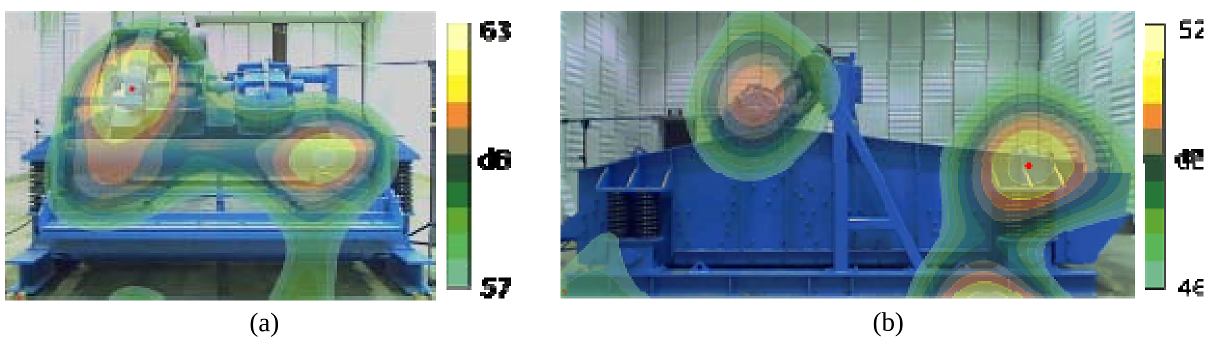


Figure 12: Narrowband results from 1.14 to 1.2 kHz for (a) the discharge end and (b) the left side.

Figure 13 shows the beamforming results summed over the 1.6 kHz 1/3-octave band. Each of the end views shows the right vibration mechanism to be a dominant source. The side views also show the area around the belt guard and vibration mechanism at the dominant sources. In addition, the left view shows the feed end coil springs to be a significant source.

The beamforming results summed across the 2 kHz 1/3-octave band are shown in Figure 14. The images show the vibration mechanisms are the dominant sources for this band. The view from the discharge end shows both mechanisms are significant for this frequency band. The spot located above the screen side on the left view is probably the result of a reflection.

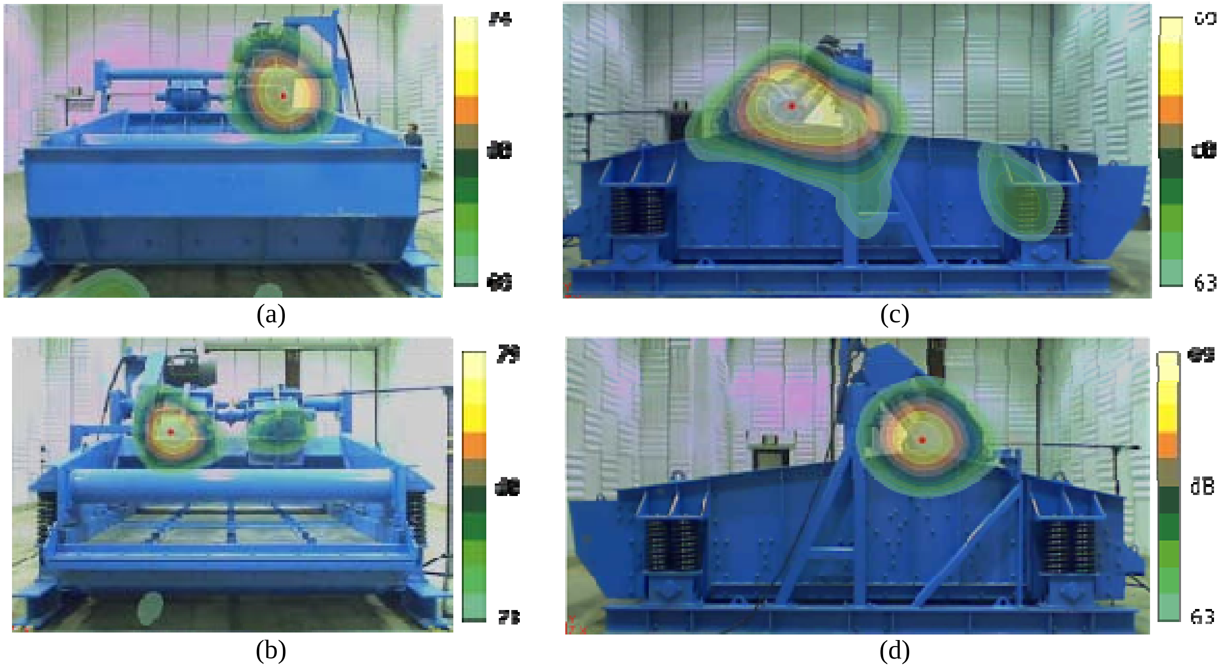


Figure 13: Results for the 1.6 kHz 1/3-octave band - (a) feed end (b) discharge end (c) left side and (d) right side.

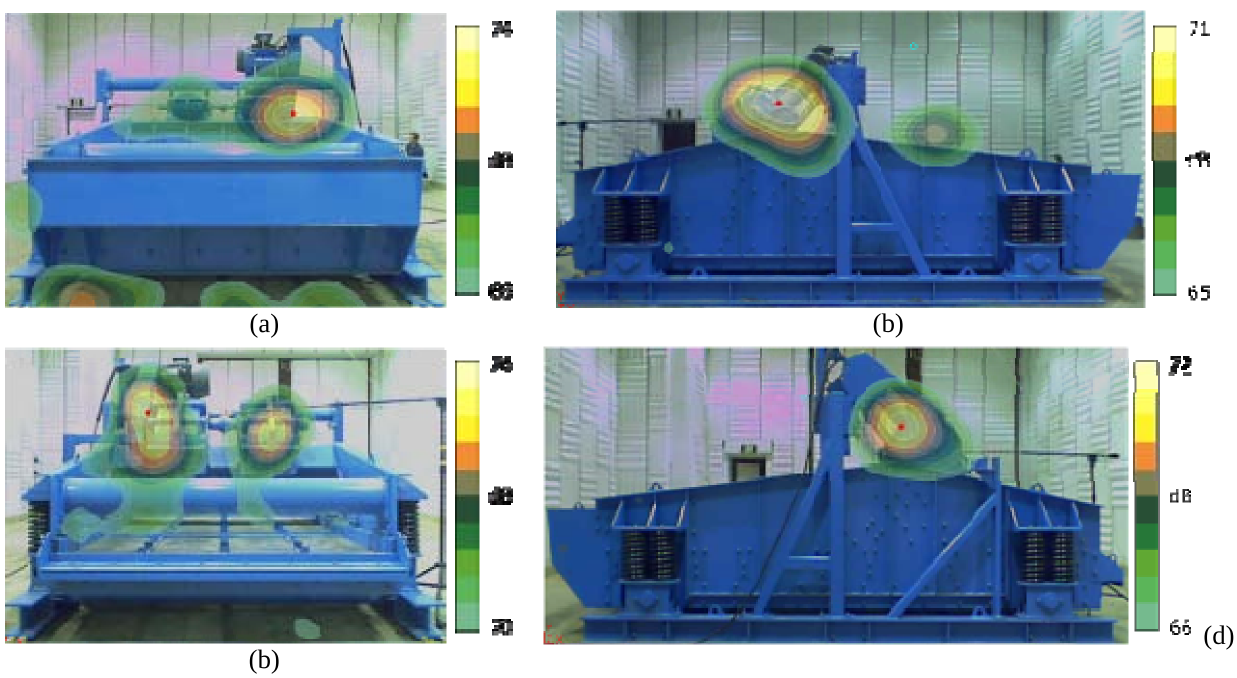


Figure 14: Results for the 2 kHz 1/3-octave band - (a) feed end (b) discharge end (c) left side and (d) right side.

Figures 15 and 16 show the beamforming results for the 2.5 kHz 1/3-octave band and the 3.15 kHz 1/3-octave band, respectively. Once again the images indicate the vibration mechanisms the belt guard are the dominant sources. The views from the discharge end show the right vibration mechanism is more significant than the left vibration mechanism for each of these 1/3-octave bands.

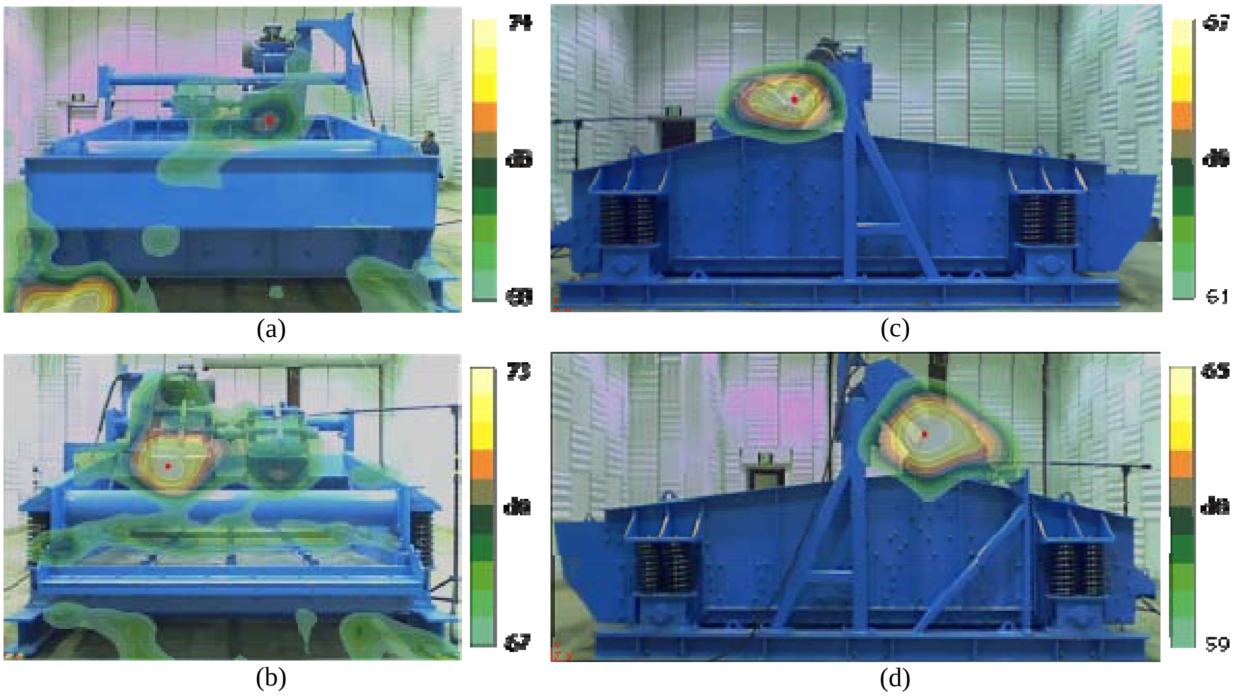


Figure 15: Results for the 2.5 kHz 1/3-octave band - (a) feed end (b) discharge end (c) left side and (d) right side.

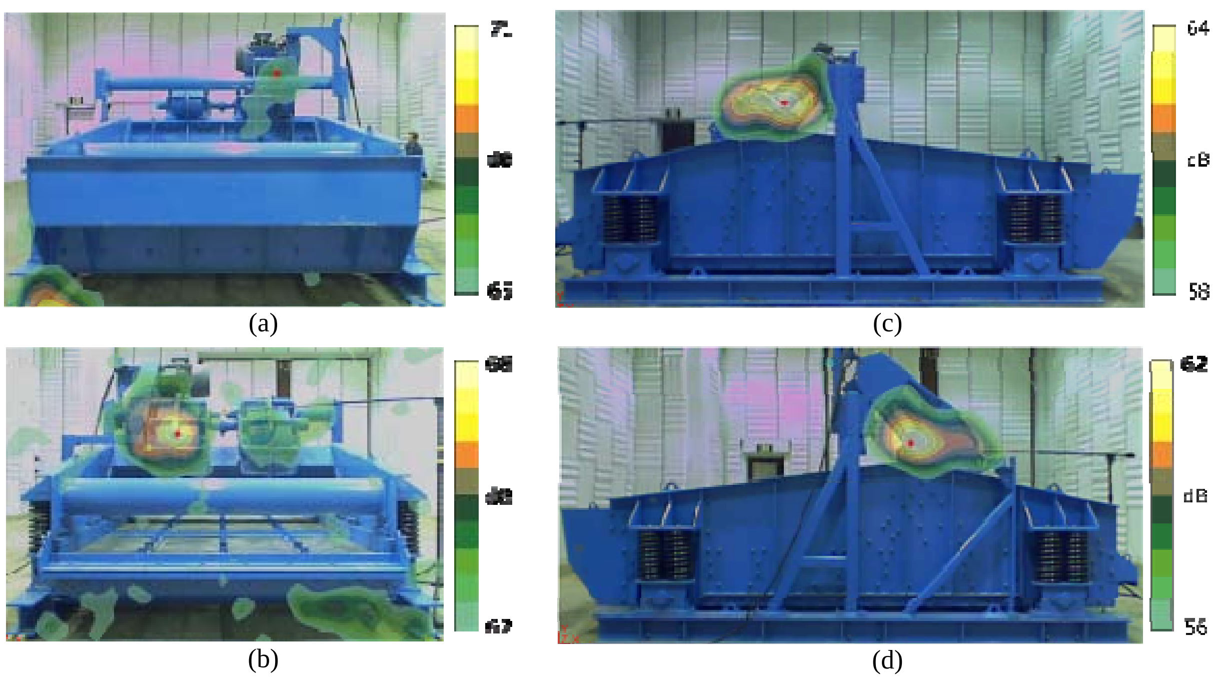
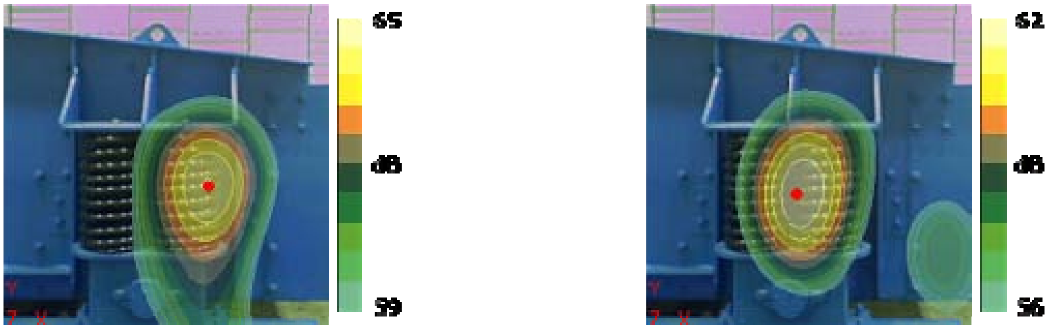


Figure 16: Results for the 3.15 kHz 1/3-octave band - (a) feed end (b) discharge end (c) left side and (d) right side.

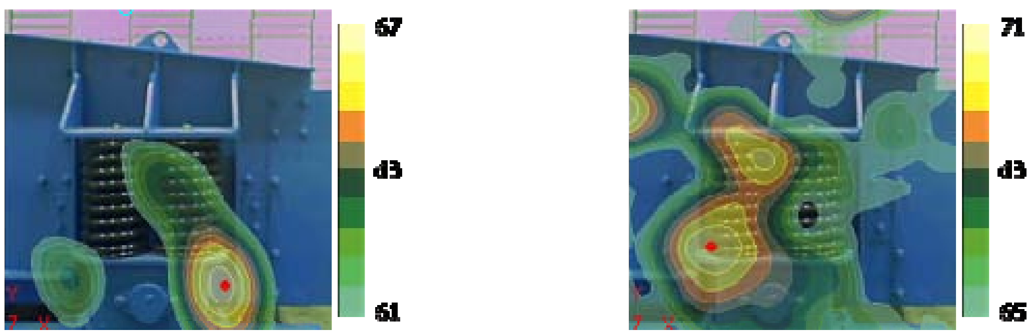
Since the coil springs at the feed end of the machine appeared to be significant sources for several frequency bands, the measurements collected 2.3 meters from the screen side were processed to examine the feed end coil springs on the left side of the screen. Figure 17 shows the beamforming results for the 1.28 kHz and 1.41 kHz narrowbands which are in the 1.25 kHz 1/3-octave band. The results show the rear-most coil spring is the most significant source for this frequency range. The rear-most spring is a single spring and the front-most outer coil spring has a smaller coil spring inside it. The individual coils on the rear spring may touch during screen operation causing the rear spring to radiate noise.



(a) (b)

Figure 17: Narrowband beamforming results for the left side, feed end coil springs - (a) 1.28 kHz and (b) 1.41 kHz.

The narrowband beamforming results for the springs for 1.63 kHz and the range from 1.66 through 1.79 kHz are shown in Figure 18 (a) and (b) respectively. For the 1.63 kHz band, the dominant sources do not appear to correspond to a real source on the screen. However, upon closer review, the high sources correspond to the openings in the spring support base (refer to Figure 19).



(a) (b)

Figure 18: Beamforming results for the left side, feed end coil springs - (a) 1.63 kHz and (b) 1.66 - 1.79 kHz.

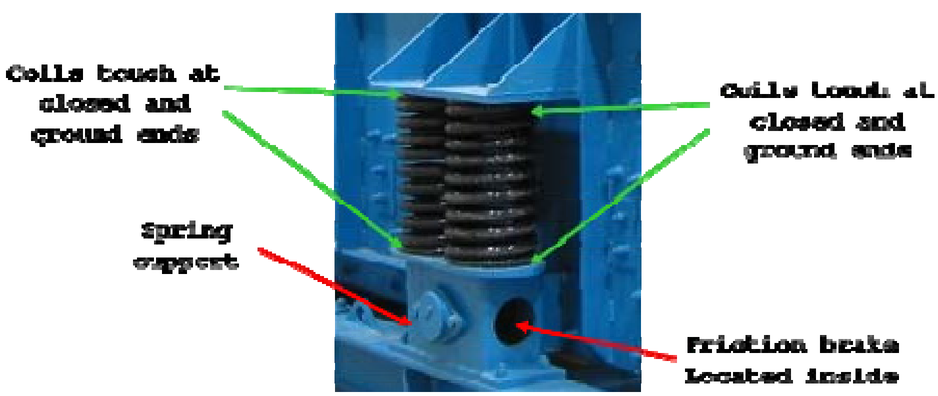
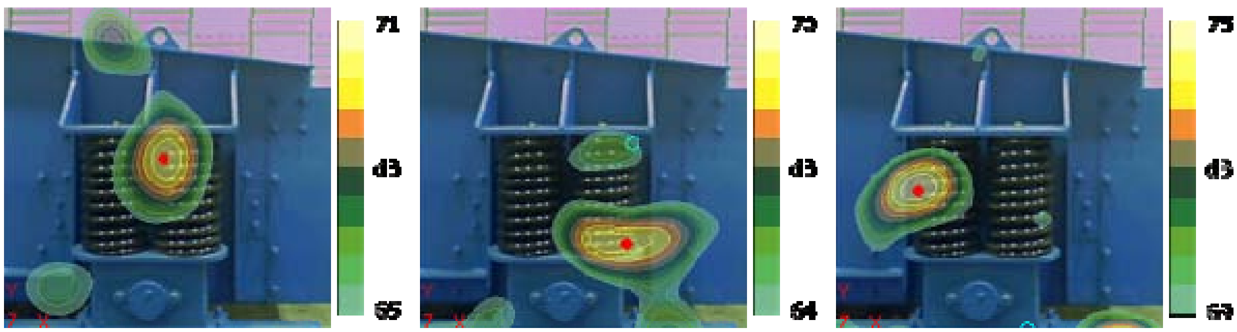


Figure 19: Vibrating screen left side, fend end spring support.

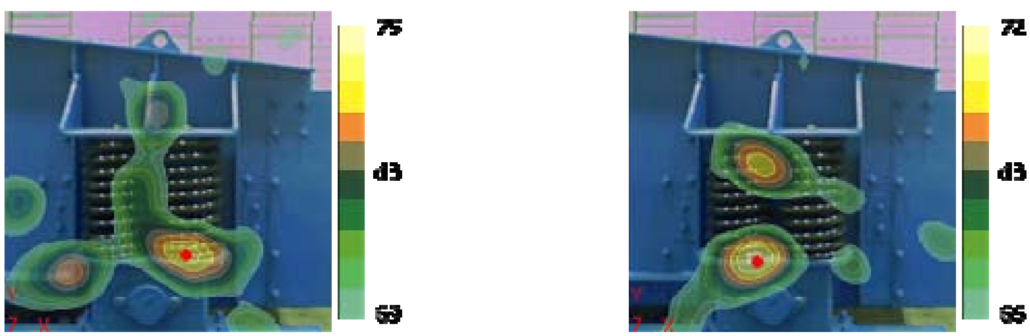
Within the spring support, an additional coil spring is used to press a urethane disc against the screen to act as a friction brake during screen start up and shutdown. The noise radiated from within the spring support base causes the appearance of the spots in Figure 18 (a). Figure 18 (b) shows the front-most coil spring to be the most significant source. The cause of noise radiation for this upper portion could be contact between individual coils from the outer spring, contact between the inner and outer spring, or contact at the closed and ground ends of the coil spring. For the lower part of the spring near the support, contact between the coils at the closed and ground spring ends appears to be the source of noise.

The narrowband beamforming results for the 1.95 through 2.02 kHz, 2.08 through 2.14 kHz, and 2.18 through 2.24 kHz are shown in Figure 20 (a), (b), and (c), respectively. Figure 21 shows the narrowband results for the 2.34 through 2.43 kHz and 2.5 through 2.56 kHz frequency ranges. Figures 20(b), 21 (a), and 21 (b) indicate that contact at the closed and ground spring ends is the dominant source for their respective frequencies. Figures 20 (a) and 20 (c) exhibit dominant sources at locations away from the spring ends. This indicates contact between adjacent coils or contact between the inner and outer spring are the cause of noise.



(a) (b) (c)

Figure 20: Beamforming results for (a) 1.95 - 2.02 kHz, (b) 2.08 - 2.14 kHz, and (c) 2.18 - 2.24 kHz.



(a) (b)

Figure 21: **B**eamforming results for (a) 2.34 - 2.43 kHz (b) 2.5 - 2.56 kHz.

4. POTENTIAL NOISE CONTROLS

The beamforming results indicate the belt guard, vibration mechanisms, and coil springs used for the screen suspension are the dominant noise sources for the 1/3-octave bands at and above 1 kHz. The beamforming results show that belt guard noise is present even when rattling is not noticeable to the ear. In addition, the sound power level results show belt guard rattling has the potential to increase the radiated noise by nearly 10 dB. Belt guard rattling can be minimized by increasing the clearance between the belt guard and the mechanism support beam. In addition, using expanded metal or perforated metal for the entire belt guard could prevent the belt guard from radiating noise. Further options include vibration isolating the belt guard or using a vibration damping material to reduce belt guard vibration. Noise from the vibration mechanism housings can be addressed by using lower noise bearings and/or gears within the mechanisms or by using a well-designed enclosure to surround the mechanisms. Alternate bearing and gear designs could be effective, but the cost associated with them may be significantly more than that of an enclosure. Another benefit to an enclosure is that it could be retrofit onto existing machines. There are several options to reduce noise from the coil springs. First, the springs could be encapsulated in a compliant material to prevent contact within the coils. Second, the space between the inner and outer springs could be increased by using a larger outer coil spring with a different wire diameter to increase the clearance but to maintain the same spring rate. Third, the coil springs could be replaced with rubber isolation mounts designed to maintain the existing spring rate at each mounting location. NIOSH measurements in an operating coal preparation plant indicated rubber isolators were beneficial in terms of noise, but could cause an unacceptable increase in building vibration if the spring rates do not match those of the steel coil springs.[8]

5. CONCLUSIONS

Sound power level measurements showed the A-weighted sound power level of the vibrating screen was 100.6 dB without noticeable belt guard rattling. Belt guard rattling increased the A-weighted sound power level to 108.3 dB when the sound power level was measured with the screen on vibration isolation pads due to the loss in frame rail stiffness. Without noticeable belt guard rattling, the frequencies at and below the 800 Hz 1/3-octave band accounted for 82% of the overall A-weighted sound power level and the 1 kHz through 5 kHz 1/3-octave bands accounted for 16% of the overall A-weighted sound power level. The noise sources in both of these frequency ranges must be addressed to reach NIOSH's goal of a 10 dB reduction. Beamforming results for the 1 kHz through 3.15 kHz frequency range identified the vibration mechanisms, belt guard, and steel coil springs as the dominant noise sources. Noise controls that reduce the contributions of each of these noise sources must be developed to achieve the desired 10-dB reduction in the A-weighted sound power level.

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