Correlating Noise Sources Identified by Beamforming with Sound Power Measurements

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ABSTRACT

Farfield beamforming is a powerful tool for identifying spatially distributed noise sources. The technique yields an image of the relative sound levels within the measurement aperture. The latest version of the beamforming software is now able to estimate the total power within its measurement aperture. In this work, the noise sources on three types of construction equipment are imaged with a beamforming array, while simultaneously the radiated sound powers are determined by a six-microphone hemisphere per ISO 6393 or ISO 6395. Of particular interest are: noise induced by turbulent flow at the exit of an exhaust stack, the effect of a noise reduction package in the engine compartment, and crawler track noise during motion. The absolute levels of the mapped source regions are compared with the total radiated sound power.

INTRODUCTION

This study was undertaken in an effort to identify and quantify key noise sources on earth-moving machinery. In general, sound power is the choice for comparing and analyzing the sound radiated into the environment by these machines. The method typically used to acquire sound power levels involves measuring sound pressure levels over an imaginary hemisphere surrounding the machine over a reflecting plane. This technique is quite useful for estimating the overall A-weighted sound power level, and it can be extended to 1/3-octave band analysis with some limitations. This technique is frequently used to characterize the contributions of major noise sources on the machine. However, it tends to be uneconomical to get beyond a few major sources.

The desire to spatially localize and quantify sources based on frequency content led us to consider beamforming methods. For various reasons, nearfield acoustical holography (NAH) typically is not practical as a means of accomplishing characterization on earth-moving machines. However, the advent of farfield beamforming presented an opportunity to analyze the major noise sources with comparatively little effort.

A commercial implementation of farfield beamforming for noise source localization was introduced by Christensen and Hald [1]. This technique involved the use of an optimally-spaced array of microphones situated throughout a circle on one plane surface. The channel count for such an array is relatively high and requires simultaneous digital acquisition. However, the aperture is sufficiently large to encompass the major noise sources of the machines, and sound field images can be acquired in a few seconds.

The original implementation of the beamformer did not provide absolute calibration of the imaged sound field. The results were presented as relative sound levels over the aperture. That enabled localization, but did not necessarily meet our goals for source characterization. As a result, we decided to measure the radiated sound power from each machine at the same time that we acquired sound field images over that machine. In this way, the sound field images could be correlated to absolute levels. Note that the beamforming system has since been extended to estimate power in its aperture [2], and this extension is compared here to qualify the final results.

One drawback of the beamforming technique is its limitation to relatively high frequencies (above several hundred cycles per second). The major noise sources on earth-moving machines tend to be in the range from 100 to 500 Hz. However, standard measurements and regulatory requirements focus on A-weighted levels, which emphasize sources from 800-4000 Hz while strongly suppressing sources below 500 Hz. Thus, from the point of view of an "A-weighted listener", the farfield beamformer is a viable method for locating and quantifying noise sources on earth-moving machines.

CHARACTERIZING SOUND EMITTED BY EARTH-MOVING MACHINERY

MEASURING RADIATED SOUND POWER

In practice, the sound emitted by earth-moving machinery is quantified in terms of A-weighted sound power level, L_{WA}. The sound power is determined in a free field over a reflecting plane per international standards ISO 6393 [3] and ISO 6395 [4]. Both of these methods estimate radiated sound power from measurements of sound pressure at six microphones whose centers intersect an imaginary hemisphere which fully encloses the machine under test. This technique is derived from a parent standard, ISO 3744 [5].

In ISO 6393, the machine sits statically in the center of the hemisphere, and the engine is operated with no load at "rated" speed, that is, the speed at which the net power of the machine is rated (typically about 90% of maximum throttle). Measurements are taken over a paved surface for all machine types.

In ISO 6395, the machine is driven on a lane through the center of the hemisphere at low speed while the engine is at maximum throttle. The sound levels are averaged during the period that the center of the machine is within the bounding hemisphere. Additionally, machines such as four-wheel-drive loaders and backhoes must actuate their primary attachment (loader bucket or backhoe) while running at maximum throttle in the center of the hemisphere. The standard gives formulas for combining forward and reverse drive levels with actuation levels. In the case of rubber-tired machines, the transit takes place over a paved surface. For tracked machines, a separate sand lane is used.

In both measurements, the result is overall A-weighted sound power. However, simultaneous acquisition through a bank of 1/3-octave band filters enables constant-percentage bandwidth spectral analysis.

GROSS ESTIMATION OF NOISE SOURCE CONTRIBUTIONS

Using the methods outlined in the previous section, a noise source allocation can be performed for major systems on the machine. Assuming they are mutually incoherent, contributions by each system (both in decibels and as a percent of total radiated power) are determined by subtraction:

$$W_{Total} = \sum_i W_i$$

$$W_j = W_{Total} - \sum_{i \ne j} W_i$$

Here, total sound power W_{Total} is the sum of (assumed incoherent) sources W_i. In particular, following a

measurement of the entire machine, major systems are disabled, and the sound power is measured again. The contribution of the disabled system is assumed to make up the difference between the measured levels.

It is quite easy to find the contributions of the cooling system and the engine exhaust, both of which tend to be major noise sources. For the former, the fan can be removed or its power source disabled. For the latter, an oversized muffler with extremely high insertion loss is attached. Beyond that, however, additional subtraction is usually very difficult. For a static test, hydraulic pumps can be disabled, but that is typically not possible for dynamic testing. The same is true for radiation from the engine itself. In these cases, wrapping the sources with high transmission-loss barrier can help, but this process is time consuming, uneconomical, and often not effective.

ACOUSTIC BEAMFORMING AS AN ALTERNATIVE

This situation leads to a desire for a non-contact method of estimating noise source contributions based on their spatial locations. On most earth-moving machines, sources, while some are coherent (i.e., related to engine rotation via some ratio), are well separated in space and have specific frequency characteristics. Given this, one possibility is to use array acoustics to evaluate the spatial distribution and frequency-dependence of noise sources.

Because the machines under consideration are quite large and the sources well removed from the outermost parts (wheels, tracks, and so on), use of a nearfield technique is impractical. The availability of a farfield beamforming system that can acquire an image of a sizeable sound field in a matter of seconds presents an attractive alternative for noise source allocation.

MEASUREMENTS

The work reported here was conducted at the John Deere Dubuque Works outdoor sound test facility. The facility consists of a concrete pad with dimensions sufficient to accommodate a 16 m hemisphere and its associated drive lane, a sand lane adjacent to the pad, and a six-microphone digital acquisition system (with two of the microphones on pneumatic towers).

For each machine and test configuration, the sound power was determined (via ISO 6393 or 6395 as appropriate) once the machine had reached operating temperatures. Immediately following the power measurement, the beamforming array was used to acquire sound field images for each of four ground-level views (front, right, rear, and left). As soon afterward as practicable, an additional image was acquired above the test machine.

For the ground-level images, the array was mounted on a simple vertical stand located 15 m from the designated measurement plane near the center of the

sound pad, as shown in Figure 1. To present each face in turn to the array, the machine was moved until that face was aligned with the measurement plane. The synthetic aperture of the array was registered to the physical space of the machine using a broadband reference sound level source. The source was located at two opposite corners of the aperture window, usually one on the pad surface and a second up on the machine. The known coordinates of the source relative to the machine are then used by the software to relate the aperture to physical space.

Figure 1. At ground level, the beamforming array was located 15 m from the machine on the sound pad. The two hemisphere microphones located on pneumatic towers can be seen in the background.

For the overhead images, the array was extended out from the base of a hydraulic boom-type man lift as shown in Figure 2. Using the lift enabled the operator to better position the array. It also allowed the cables from the array microphones to remain at a reasonable length. Typically, the array was positioned about 9 m from the ground, leaving about 6-7 m to the noise source plane. (The machine operating stations intruded through the measurement plane. However, since they contributed essentially nothing to the sound power, their presence did not affect the measurements.)

Beamforming reconstructions shown in this paper were typically done on a grid spaced 0.2 meters horizontally and vertically within each side aperture, and 0.1 meters for top apertures. The near-axial resolution of the beamforming algorithm [1] is

$$R_{beam} \approx 1.22 \frac{L}{D} \lambda,$$

where L is the distance from the array center to the measurement surface, D is the diameter of the array, and λ is the wavelength of sound at the frequency of interest. For the setup described here, L=15 m, D=1 m, and λ ranges from 0.7 m to 0.07 m, yielding resolutions

ranging from about 12 m at 500 Hz to about 1.2 m at 5000 Hz. This relatively poor resolution was driven by the need to capture the entire machine within the aperture; concentrating on smaller areas of the machine and reducing L would have improved the resolution.

Figure 2. A man lift was used to suspend the array above the machines for the top view.

RESULTS

Three machine types were investigated. These included a motor grader, a production-class four-wheel-drive loader, and a utility-class crawler-dozer. For the motor grader, the noise source of interest was a high-frequency, broadband noise attributed to turbulent gas emission from the exhaust stack. The effect of a sound-absorption package in the engine compartment was studied on the loader. On the crawler, an attempt was made to capture the dynamic track noise while the machine drove past the beamformer.

EXHAUST STREAM NOISE

Figure 3 shows intensity reconstruction results from the Motor Grader idling at rated speed (2000 RPM). The contour map shows a bloom from 2500 Hz to 5000 Hz about 1 m past the exhaust stack. This indicates turbulent noise generation in the shear layer where hot exhaust gas is interacting with cool ambient air. This is the dominant noise source in this frequency region.

The chart in Figure 4 compares the 1/3-octave band sound power levels computed from the sum of the five

reconstructed surfaces (top, left, right, front, and rear) to those measured directly from the sound pad hemisphere. The overall (linear) levels are within ½ dB of each other. However, it is clear that in bands above 2000 Hz, beamforming begins to overestimate the total levels due to sidelobes in the reconstruction aperture.
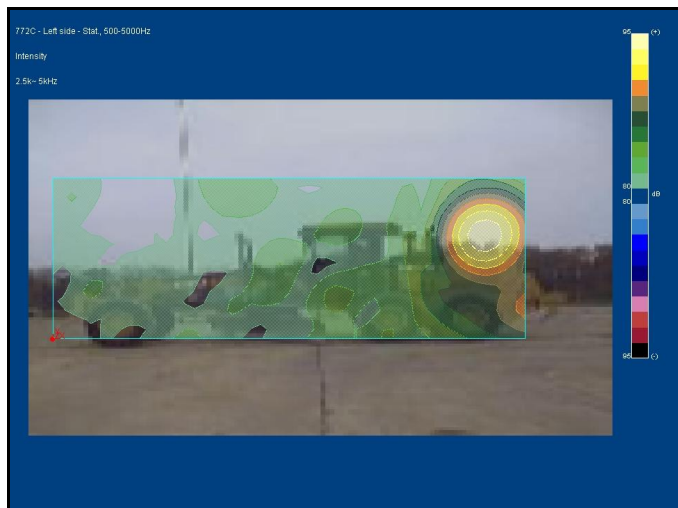

Figure 3. Reconstruction of the intensity field intersecting the left side of the motor grader spanning from 2.5 kHz to 5 kHz. The color map extends from 80 to 95 dB re 1 pW/m^2.
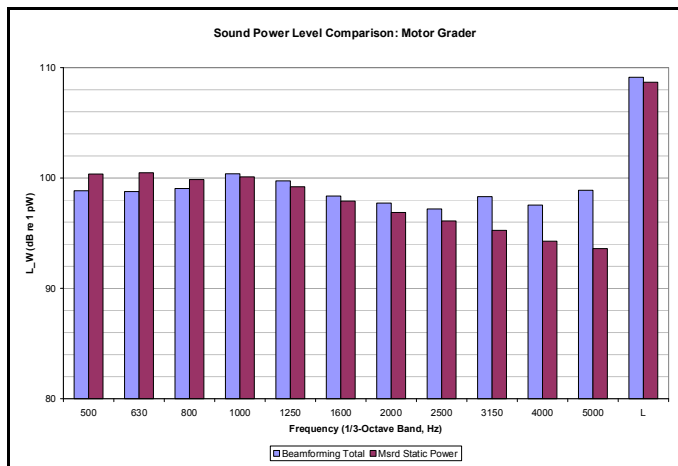
Figure 4. Sound Power Levels in 1/3-Octave bands and Linear Overall comparing the computed results from beamforming (light/blue) to measured results from ISO 6393 (dark/red) for the Motor Grader at maximum throttle.

NOISE TREATMENT IN AN ENGINE ENCLOSURE

Figure 5 shows results from a production-class four-wheel-drive loader idling at rated speed (2100 RPM). Taken as a "baseline", this reconstruction can be compared with that of Figure 6, after the engine compartment has been treated with a noise control package. The color scales are the same, but the peak contour for the treated machine is some 4.5 dB below that of the baseline.
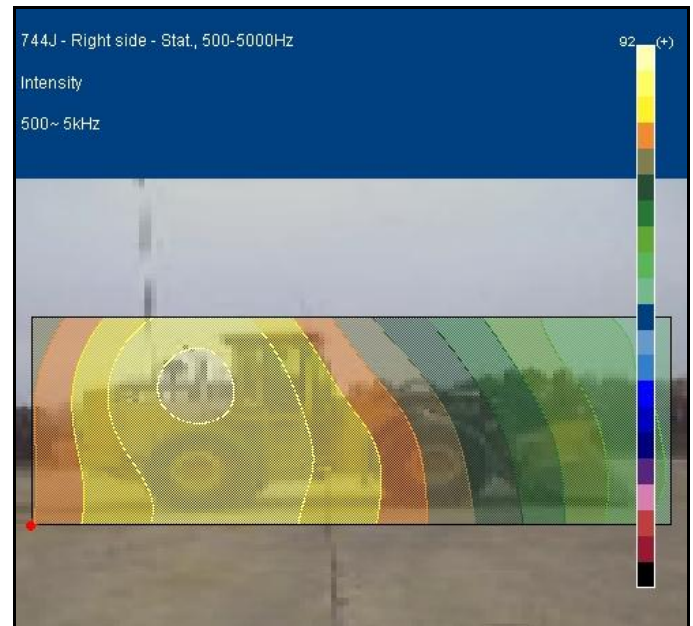

Figure 5. Reconstruction of the intensity field intersecting the left side of a 4WD Loader, spanning from 500 Hz to 5 kHz. The color map extends from 77 dB to 92 dB re 1 pW/m^2.
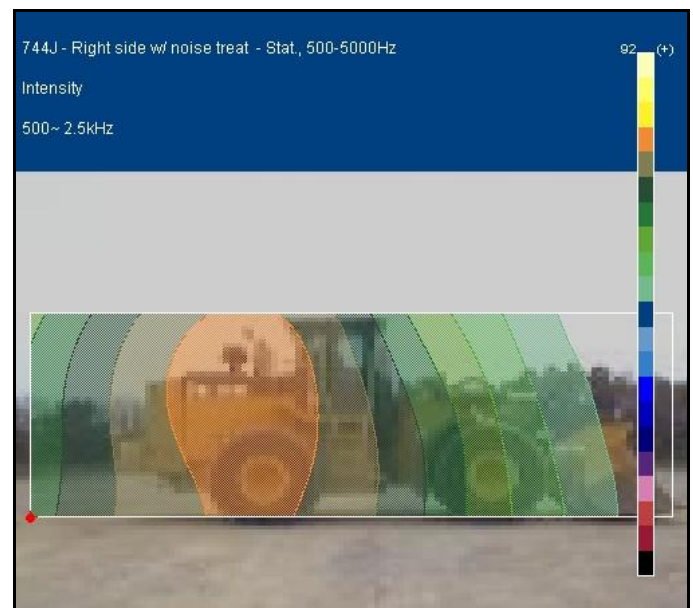

Figure 6. Reconstruction of the intensity field intersecting the left side of a 4WD Loader which has been treated with a noise control package. The color map extends from 77 dB to 92 dB re 1 pW/m^2, but the maximum contour is now 4.5 dB below that shown in Figure 5.

The spectra in Figure 7 and Figure 8 compare the power levels computed from the beamforming apertures with the measured sound power levels. The reduction of about 2 dB in overall power from introduction of the treatment package is again evident in both charts. For the untreated machine, agreement for the overall linear level is within 1 dB; for the treated machine, it is about 1.4 dB. However, as with the motor grader, the aperture measurement overestimates the bands above 2000 Hz.
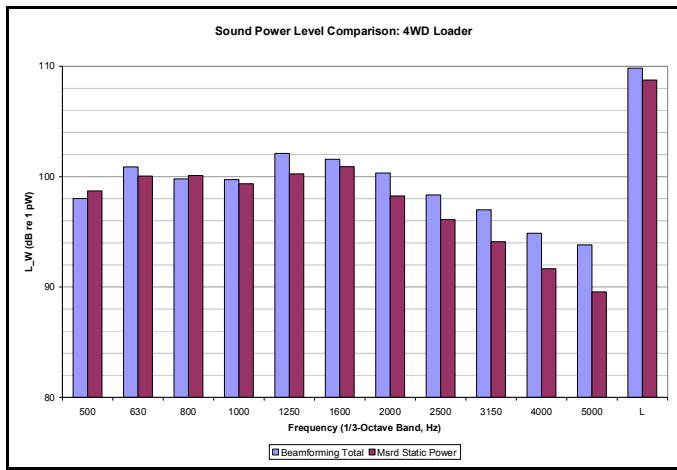
Figure 7. Sound Power Levels in 1/3-Octave bands and Linear Overall comparing the computed results from beamforming (light/blue) to measured results from ISO 6393 (dark/red) for the 4WD Loader.
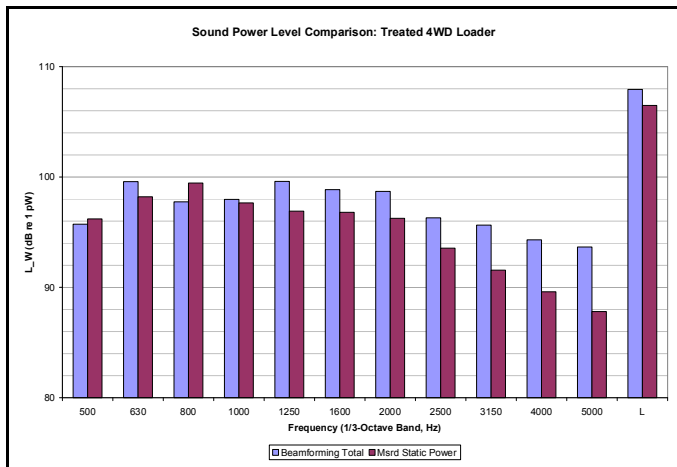

Figure 8. Sound Power Levels in 1/3-Octave bands and Linear Overall comparing the computed results from beamforming (light/blue) to measured results from ISO 6393 (dark/red) for the 4WD Loader after treating the engine compartment with noise absorption material.

The discrepancy between measured and reconstructed radiated sound power for this machine most likely has to do with the engine hood. On this loader, the engine hood is highly perforated to allow airflow into the cooling package. High frequency sound emanating from the engine and cooling package is directed upward through the hood. The tower-mounted microphones in the hemisphere may not get a full view of this noise, while the beamformer suspended directly over the hood would capture it all. However, removing the entire top aperture from the power sum underestimates the total power.

DYNAMIC NOISE FROM STEEL TRACKS

A third experiment was performed to capture the radiation from the undercarriage of a tracked crawler-dozer. To do this, it was necessary to conduct a driveby

with the machine. The standard for measuring sound power specifies a traverse speed not to exceed 4 km/h.

First, a static case was tested with the engine idling at rated speed (2000 RPM). The results of the reconstruction on the left side of the crawler, summing from 500 Hz to 5 kHz, are shown in Figure 9. The intensity is concentrated at the perforated side shields surrounding the engine, as expected.

Next, a driveby test was conducted, in which the beamformer collected data from before the crawler entered the aperture until after it had exited, a period of about 13 seconds. The data were processed in a "quasi-static" mode in increments of 0.5 seconds.
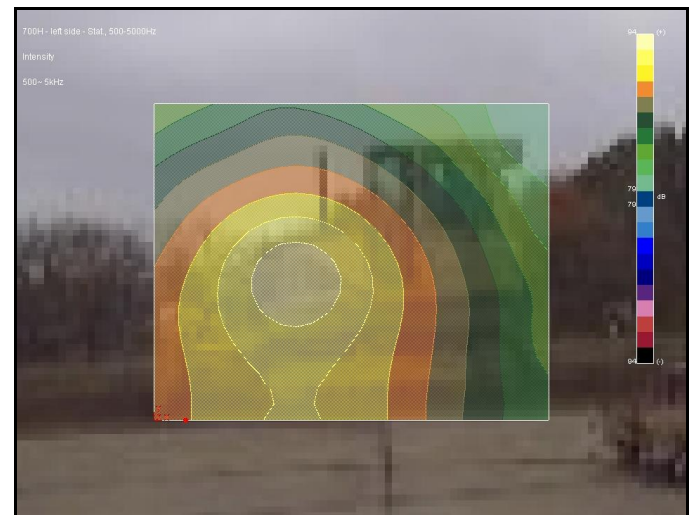

Figure 9. Reconstruction of the intensity field intersecting the left side of a crawler dozer, spanning from 500 Hz to 5 kHz. The color map extends from 79 dB to 94 dB re 1 pW/m^2.
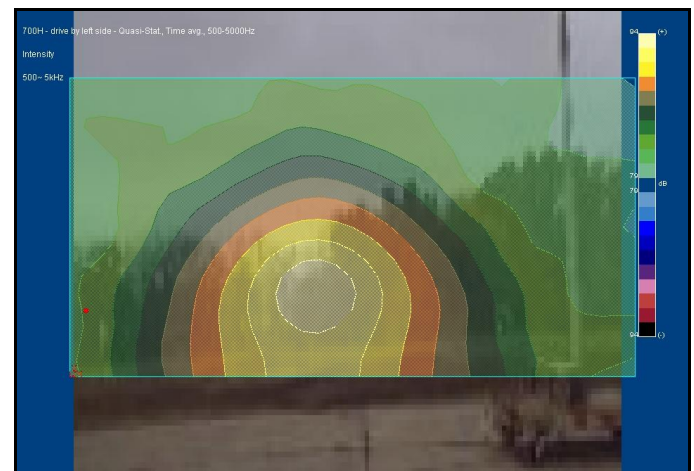

Figure 10. Reconstruction of the intensity field intersecting the left side of a crawler dozer during driveby, spanning from 500 Hz to 5 kHz. The noise from the tracks is not visible within the dynamic range. The color map extends from 79 dB to 94 dB re 1 pW/m^2.

The results, shown in Figure 10, do not reveal any activity from the tracks. In this view, the engine noise dominates the available dynamic range, and no track noise can be seen.

An alternative set of views taken from above the machine tell a different story. A static view from above the crawler is shown in Figure 11. Both the exhaust and the fan noise (reflecting from the blade) are apparent.
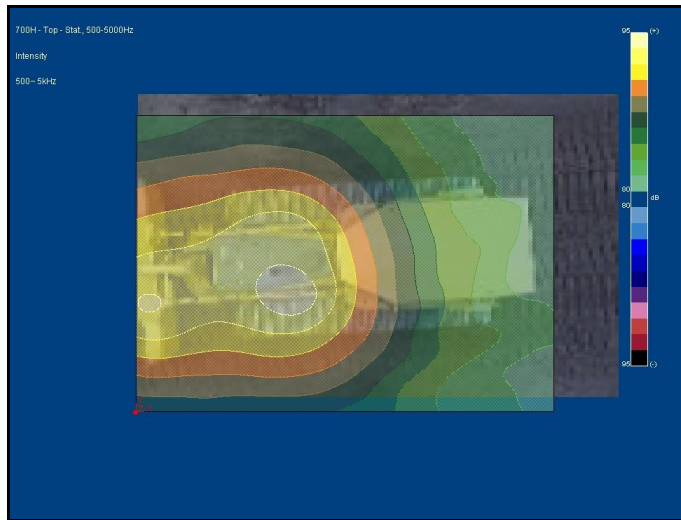

Figure 11. Reconstruction of the intensity field intersecting the hood of a crawler dozer, spanning from 500 Hz to 5 kHz. The color map extends from 80 dB to 95 dB re 1 pW/m^2.

In a similar view taken during the driveby, the same pattern is seen, presumably with the same dominant sources. The tracks are not apparent in this broadband view in which the engine and fan noises dominate.
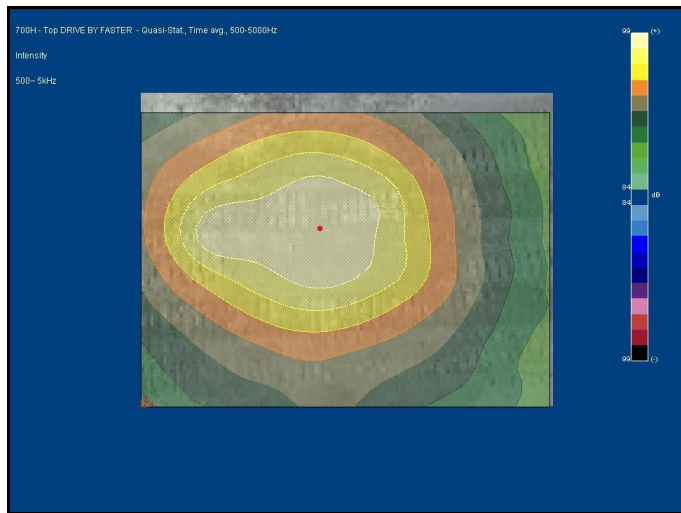

Figure 12. Reconstruction of the intensity field intersecting the hood of a crawler dozer during driveby, spanning from 500 Hz to 5 kHz. Note the similarity to the static case above. The color map extends from 84 dB to 99 dB re 1 pW/m^2.

However, once the engine leaves the aperture, the track noise becomes visible. This is shown in Figure 13. The exhaust still dominates, but two long lobes clearly indicate the tracks. They become even more evident when the intensity is confined to the 3.15 kHz band, shown in Figure 14. Here, both spur gear/final drive (near top center on the map) and the top idler (toward the left, above and below) can be seen as they interact with the track shoes.
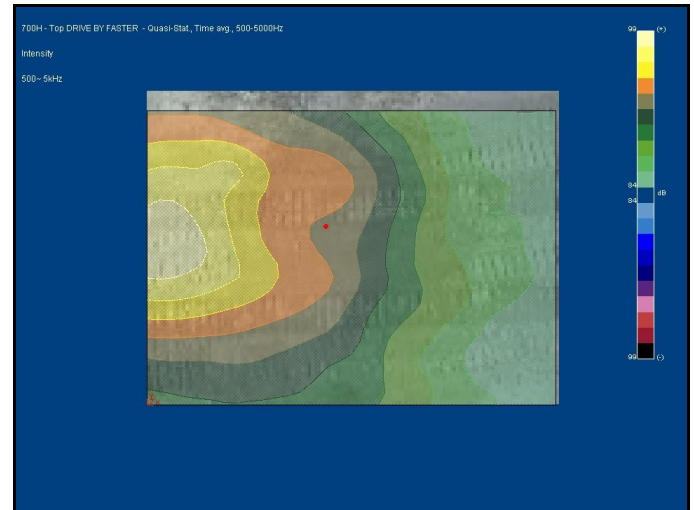

Figure 13. Reconstruction of the intensity field intersecting the hood of a crawler dozer during driveby as the engine is exiting the aperture, spanning from 500 Hz to 5 kHz. The contribution from the tracks is visible. The color map extends from 84 dB to 99 dB re 1 pW/m^2.
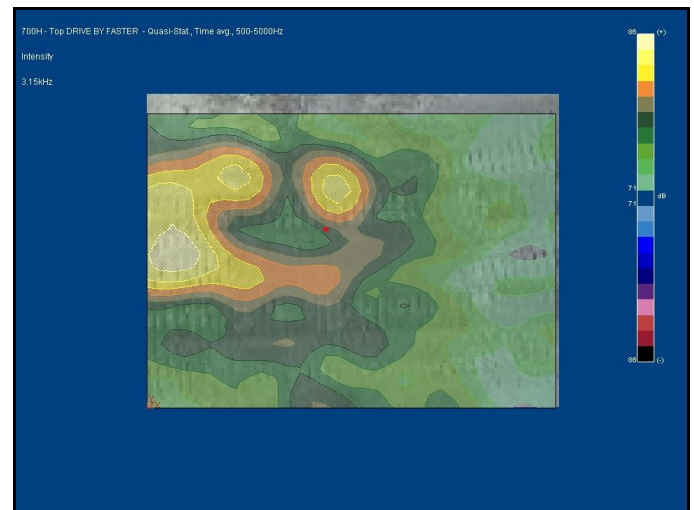

Figure 14. Reconstruction of the intensity field intersecting the hood of a crawler dozer during driveby as the engine is exiting the aperture, in the 3.15 kHz 1/3-octave band. The main spur gear and top idler interactions are visible for both tracks. The color map extends from 84 dB to 99 dB re 1 pW/m^2.

When comparing measured and reconstructed total sound power for the crawler dozer, the chart in Figure 15 tells a different story from the results for the loader and grader. In this case, the beamforming does not overestimate the higher bands. It does, however, underestimate the power in the 500, 630, and 800 Hz bands. It has not been determined why this occurred.
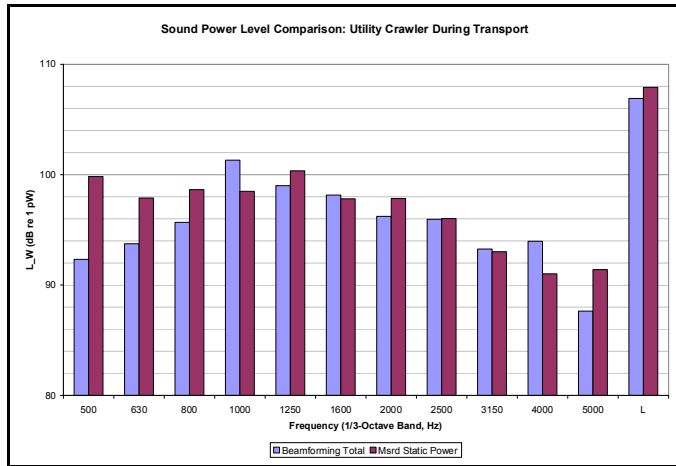

Figure 15. Sound Power Levels in 1/3-Octave bands and Linear Overall comparing the computed results from beamforming (light/blue) to measured results from ISO 6393 (dark/red) for the Utility Crawler while transiting past the array.

CONCLUSION

This work demonstrates for the first time the application of farfield beamforming to estimate sound power levels from large earth-moving machines while in the field. The simultaneous measurement of sound power using standard techniques gave a direct comparison. In all three experiments, the beamformed estimate agreed very well with the measured power over the full spectrum. In two of three cases, the beamformed estimate of radiated power was slightly higher in bands above 2500 Hz. These discrepancies are most likely due to inclusion of sidelobes in the integration aperture. In another case, it overestimated power in bands below 800 Hz. This effect is not currently understood. The distance to the measurement surface was large in order to capture the entire machine within the array aperture; this led to relatively poor spatial resolution in reconstruction. Even so, beamforming yielded valuable information on the location and frequency content of specific sources of sound power on the construction equipment tested.

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