11NVC-0125

Vibro-Acoustic Source-Path-Receiver approach to Identifying and Troubleshooting in an Agricultural Tractor Mode Coupling Issue

G. Pietila, G. Cerrato
Sound Answers

B. Tadlock, B. Kascht, S. Entriken
AGCO

ABSTRACT

As an agricultural tractor OEM was moving a new tractor model from development into production, an objectionable cab "boom" was identified that was not present in the preproduction pilot -level tractors. The cab boom was identified as a low frequency tone causing an increase of 7 (dBA) over the level in the pilot tractors, which was deemed unacceptable. The process used by the tractor OEM engineering team to address this problem has been widely used and refined in the automotive industry, but it is relatively new in the agricultural/off-road vehicle industry. This paper describes the source-path-receiver approach that led to identifying the exhaust tip as the source and the vibro-acoustic coupling of a windshield structural mode with an acoustic cab cavity mode as the path of the boom event. Data are also presented in support of the interpretation of the noise generation mechanisms and to validate countermeasures focused on source and path sensitivity reduction strategies, such as frequency shifting and mode decoupling by use of lumped masses and ¼ wavelength tuner.

INTRODUCTION

A commercially available agricultural tractor was found to exhibit a cab "boom" event when the engine speed was swept through the operating range. This "boom" event was characterized as a significant increase in the sound pressure level (SPL) measured at the driver's ear location in the 1800-2040 rpm engine speed range.

The tractor OEM engineering team used a source-path-receiver approach to identify the root cause of the "boom" event, and to develop potential countermeasures to reduce its effect. The source-path-receiver approach discussed in this paper is presented with the understanding that the SPL observed at the driver's position, the receiver, is a function of the source level as well as the sensitivity of the path to the given source. Using this approach, in a noise and vibration application, the path sensitivity is generally quantified in terms of a response level, in terms of sound pressure or acceleration, normalized by an excitation level, in terms of force or pressure, often denoted as A/F (acceleration divided by excitation force), P/F (sound pressure divided by excitation force), P/P (sound pressure divided by excitation pressure), ect. In most cases the model can be broken up into different path sensitivities, for different paths, as well as different sensitivities for different legs in the same path.

The goal of this source-path-receiver approach is to identify the most efficient way to reduce the observed response at the receiver position, the SPL at the driver's ear in this case. In general the most preferred solution is to identify and reduce the source itself. In some cases, where countermeasures applied directly to the source are limited or even not feasible, it becomes necessary to implement countermeasures that reduce the path sensitivity. Finally the least preferred solution is to address the response level at the receiver itself, such as applying hearing protection to the driver in this case. Various troubleshooting approaches are discussed in the reference papers [1-3].

TROUBLESHOOTING PROCESS

The boom event, as described earlier, is shown in Figure 1, which shows the SPL measured at the driver's ear for a production level tractor with the boom event compared to a pilot level tractor with no boom event. One can see that there is a significant increase in SPL as the engine speed passes through the 1700-1900 rpm speed range. This type of event is generally a result of a strong forcing function, in this case the 3rd engine order (EO) or firing frequency, passing through a system natural frequency. The 3rd EO is suspected based on the understanding that the engine is a 6 cylinder diesel engine, so the main forcing function, cylinder firing, is expected to occur 3 times per engine revolution, or 3rd EO. If the 3rd EO is the main forcing function one can estimate that at 1825 rpm, the peak of the boom event, the 3rd EO passes through 91.2 Hz. The speculation regarding the 91.5 Hz resonance is confirmed by the results of the artificial excitation test presented later, Figure 4, whereas the identification of the 3rd EO as the dominate forcing function is not important based on the engine being a sourced component.

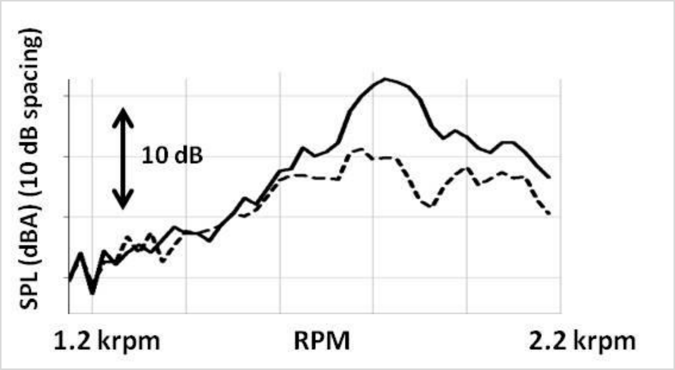

Figure 1: Comparison of a recording inside a tractor with a boom event (solid line) to a tractor with no boom event (dotted line)

Source

The engine firing frequency can excite the response at the driver's ear in two ways, structurally through the tractor chassis, or acoustically from either the exhaust tip, the intake snorkel, or it could be radiated directly from the engine. Preliminary tests with an extended exhaust tip had shown significant effect on the SPL at the driver's ear, thus identifying the exhaust tip as main source for the 3EO boom. Figure 2 shows the SPL measured at the driver's ear position as the exhaust tip is varied from 16 to 28 to 48 inches. In this plot one can easily see that as the exhaust tip is lengthened, or moved farther from the receiver position, the resulting SPL is decreased significantly. The source is therefore the noise at the exhaust tip which is being transmitted via an airborne path to the windshield, then structure-borne through the windshield and airborne again through the cab to the driver's ear.

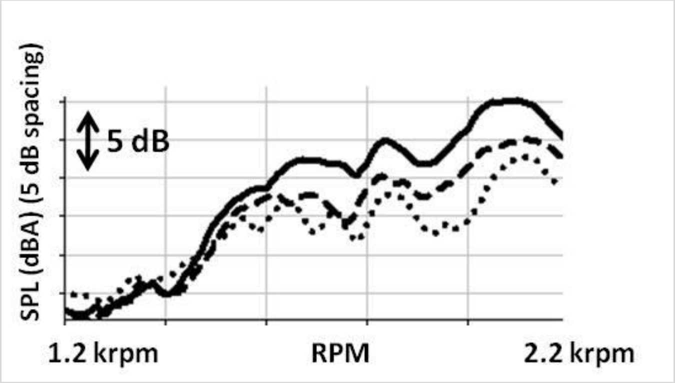

Figure 2: Comparison of overall level (measured in the cab) vs engine speed for a 16 inch (solid), 28 inch (dashed), and 48 inch (dotted) exhaust tip length.

To confirm this hypothesis an artificial acoustic excitation test was developed, using a loudspeaker, approximately at the location of the exhaust tip, to excite the cab response, Figure 3.

Figure 3: Artificial acoustic excitation used to excite the cab response.

Initially a 50-150 Hz swept sine excitation signal was directed toward the windshield and the response SPL was measured at the driver's ear locations, shown in Figure 4. This plot overlays the left (solid line) and right (dashed line) ear responses over the reference signal (dotted line). The reference signal was measured using a microphone between the cab and speaker, the scale has been adjusted to allow the three plots to be displayed on the same graph. One can easily see that the artificial acoustic excitation excites resonances at 54, 92, and 102 Hz, therefore the artificial excitation test is able to replicate the "boom" event in a lab environment eliminating the need to continue troubleshooting with full vehicle operating measurements. This allows for a more controlled test condition. This test also confirms the hypothesis that the airborne path is the most significant. A description of a similar type of test is outlined by Sanderson and Onsay [4]

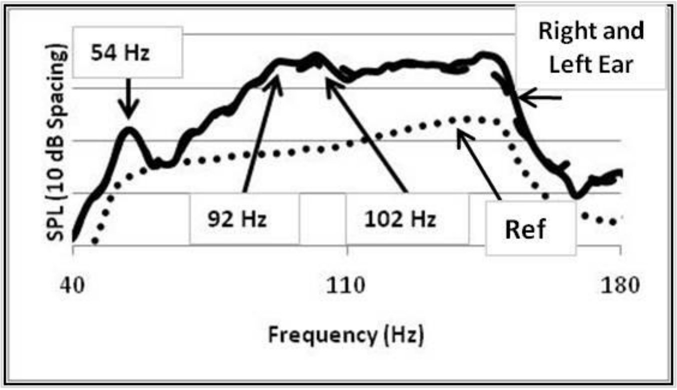

Figure 4: Driver's left (solid line) and right (dashed line) ear response to an artificial sine sweep (dotted line).

At this point it is understood that the main source of the "boom" event is the acoustic excitation from the exhaust tip, and that the level of the response can be greatly reduced by extending the length of the tip.

Path

The next step in the process is to gain a better understanding of the vehicle sensitivity, or path, to the source. Knowing that the source is the acoustic excitation from the exhaust tip, one would suspect that the main path would an acoustic path from the tip to the cab with shield, a structural path through the windshield, and an acoustic path through the cab. To confirm this impact testing was conducted on the windshield to understand its natural frequencies and mode shapes.

The impact testing was conducted using a calibrated "modal" hammer as a source and impacting 26 points that were dispersed over the windshield in a grid, and three accelerometers located at different points on the windshield. The frequency response functions (FRFs) were then estimated using the measured inputs and responses, and used to identify the frequencies and mode shapes. The FRFs measured at two points on the windshield, Figure 5, show a glass resonance at 92 Hz.

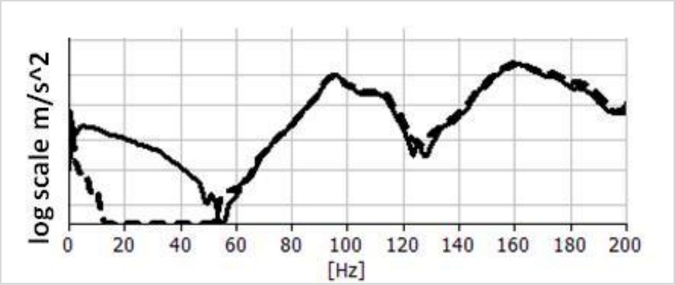

Figure 5: Frequency response function measured at two points on the windshield.

The FRFs are then used to animate the mode shape of the 92 Hz resonance, shown in Figure 6, and to identify the mode as the 2nd bending mode. Knowing the mode shape then allows the engineers to develop a countermeasure to modify the resonant frequency of the glass. In this case two masses were applied to the glass on vertical lines passing through the points of maximum motion, points A and B in Figure 6.

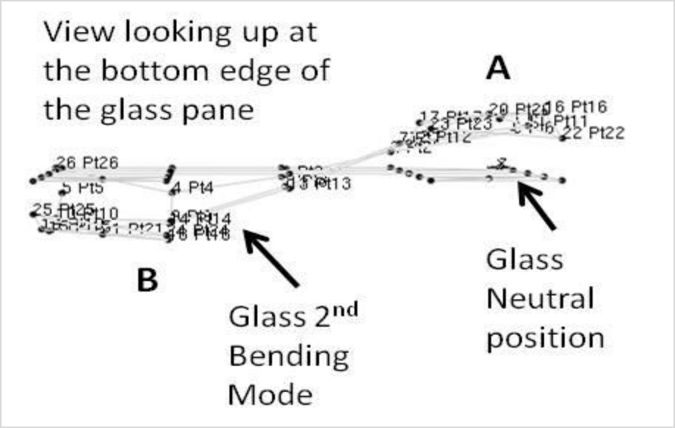

Figure 6: Glass mode shape at 92 Hz.

The masses were applied not as a feasible countermeasure, but rather to establish an indication of improvement that could be expected by modifying the glass structural response. After the masses were applied the artificial acoustic excitation measurements were rerun and are shown in Figure 7.

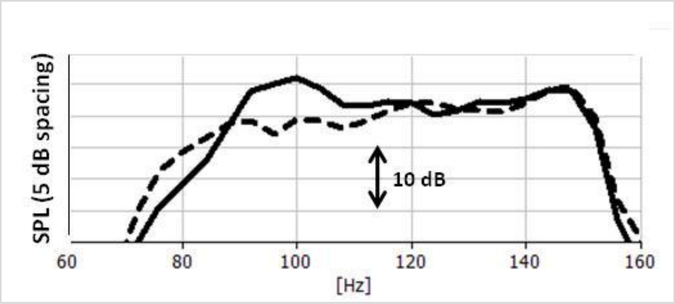

Figure 7: Comparison of the driver's right ear response before (solid line) and after (dashed line) mass was added to the glass.

In this figure one can see that adding the masses to the points with the greatest motion moved the glass resonance and reduced the response at the driver's right ear by about 5 dB.

During the artificial excitation testing it was also subjectively noticed that while the excitation signal dwelled at 102 Hz, the level of the signal in the cab changed with position, indicating a standing wave or acoustic cab mode. To confirm this, additional measurements were run with the acoustic source dwelling at 102 Hz, and the SPL was measured at various points in the cab. The schematic in Figure 8 is a cross section of the cab, and shows the measured SPL at various points in the cab, normalized by the lowest level. From this picture one can easily identify the acoustic standing wave in the cab.

To address a standing wave one of three approaches can be used: changing the cab geometry, adding absorptive material, or adding a reactive element, such as a ¼ wave length tuner or Helmholtz resonator. In this case, because of the difficulty in modifying the cab geometry, and in adding enough absorptive material in the confined space to absorb a 102 Hz wave, a ¼ wavelength tuner was built using a piece of exhaust pipe 84 cm in length, shown in Figure 9.

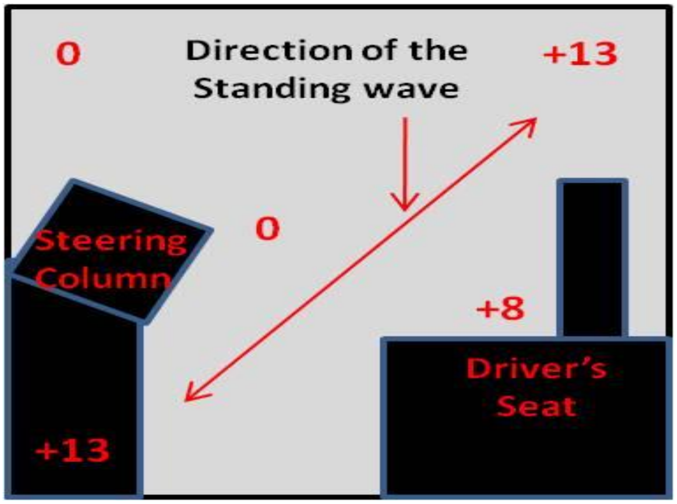

Figure 8: Schematic showing the variation in SPL during an artificial acoustic sine dwell test.

Figure 9: 84 cm 1/4 wavelength tuner designed to cancel a 102 Hz acoustic wave.

The tuner was placed in the lower front corner of the cab, or the point of maximum SPL, and the artificial acoustic test was rerun on the cab with mass applied to the windshield. The results of this test, along with the baseline and glass modification are shown in Figure 10. As shown in this figure the ¼ wavelength tuner reduces the response at 102 Hz as designed, but increases the level at 125 Hz. This response would be expected if a Helmholtz resonator was used, but is not expected for a properly designed ¼ wavelength tuner [5]. In this case the tuner was fabricated using scrap exhaust parts to gain insight into the potential gains, so it is likely that the increase at 125 Hz is a result of a poorly designed tuner. For example this could be caused by changes in cross section through the length of the tube. The final system would be optimized for packaging and response. A short discussion on acoustic tuning of vehicle interior systems is presented by Griffin , et. al. [6]

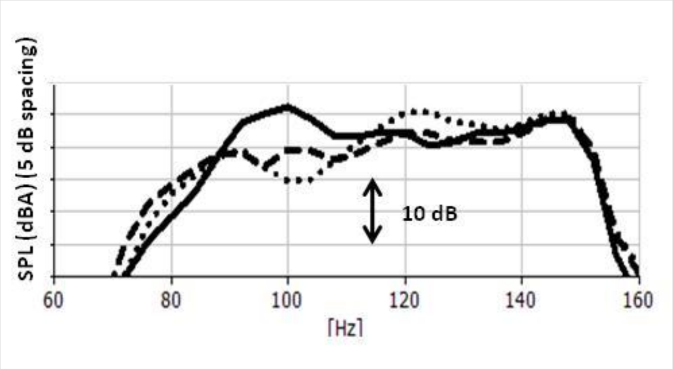

Figure 10: Comparison of the driver's right ear response for the baseline (solid line), after mass was added to the windshield (dashed line) and after a 1/4 wavelength tuner was placed in the cab (dotted line).

CONCLUSIONS

In this paper a source-path-receiver approach to troubleshooting was implemented to understand and address a cab “boom” event that was identified in an agricultural tractor. Using this approach the engineering team was able to identify the exhaust tip as the main source driving the boom, and path sensitivities in the form of vibro-acoustic coupling between a glass structural resonance and a cab acoustic mode that resulted in the boom event.

Based on these findings and practical countermeasures used for validation the engineering team was able to recommend:

- That the exhaust tip be extended as much as feasible to increase the distance between the source and the receiver, or driver’s position.
- That the glass structure be modified to shift the resonant frequency away from other component modes in the tractor, this can be accomplished by modifying the shape of the glass. A mode alignment table is a tool that is commonly used to avoid mode coupling in complex systems.
- If necessary a ¼ wavelength tuner could be packaged to cancel the 102 Hz acoustic mode.

ACKNOWLEDGMENTS

Special thanks to Mr. Mike Zimm of Bruel & Kjaer NA for his support.

REFERENCES

1. Cerrato G., Pietila G. “Noise and Sound Quality Optimization of Agricultural Machine Cab”, SAE Technical Paper 2010-01-1988, 2010.
2. Shih S., Yruma J., Kittredge P., “Drive train Noise and Vibration Troubleshooting”, SAE Technical paper 2001-01-2809, 2001
3. Lee D., Hwang W., Kim M., “Booming Noise Analysis in a Passenger Car Using a Hybrid Integrated Approach” SAE Technical Paper 2000-01-0723, 2000.
4. Sanderson M. A., Onsay T., “CAE Interior Cavity Model Validation using Acoustic Modal Analysis”, SAE Technical Paper 2007-01-2167, 2007
5. Frank Fahy, “Foundations of Engineering Acoustics”, London ,Academic Press, 2003
6. Griffin C. T., Wentzel R., Raveendra S. T., Khambete S., “Acoustic Tuning of Lightweight Vehicle Interior Systems”, SAE Technical Paper 2001-01-1628, 2001.
7. Cameron C. J., Wennhage P., Goransson P., “Prediction of NVH behavior of trimmed body components in the frequency range 100-500 Hz”, Applied Acoustics, 71 (2010) 708-721

CONTACT

Glenn Pietila
Glenn.pietila@soundanswers.net
(248)904-5153