Use of the Sound-intensity Method to Identify Acoustic Leakages from Off Highway Machine Cab

Author: Sachin Pawar, John Deere Technology Center India

, co-author (Do NOT enter this information. It will be pulled from participant tab in MyTechZone)

Affiliation (Do NOT enter this information. It will be pulled from participant tab in MyTechZone)

Abstract

The operator station or "cab" in off Highway equipment plays a critical role to provide a comfortable environment for the operator. The cab interfaces with several elements of the off-highway equipment which can create gaps and openings. These openings have the potential for acoustic energy leakage, ultimately increasing sound within the cab. During machine operation, noise generated around the cab conducts inside through these leakages resulting in increased sound levels. Acoustic leakages are among the key noise transfer paths responsible for noise inside the cab. Therefore, before considering noise control treatments it is best to first identify and minimize any leakages from joints, corners, and pass-throughs to achieve required cab noise reduction.

In this effort the sound intensity technique is used to detect the acoustic leakages in cab. The commercial test system is used for measuring the sound intensity field over objects. For the cab, an acoustic source is used inside the cab as a known energy source and the intensity levels are measured outside the cab. The test is conducted in a semi-anechoic chamber. Each external surface of the cab was scanned with a Sound-intensity probe and the leakages on each surface are detected individually. The results from this test will be used to reduce the leakages, eventually reducing the noise level inside the cab.

Introduction

A cab or operator station of off highway equipment in recent times to provides a comfortable and productive environment inside and are important areas of success as both are vital aspects of operator comfort. The most important aspect of comfort is to protect the operator from noise generated / transfer to cab by the machine subsystems such as engine, transmission, crop/grain handling mechanisms, implements and acoustic leakages. Noise Control treatment such as damping treatments, absorption textile and foam are used on the panels to reduce noise in the cab. Figure 1 shows some of the acoustic treatments used on a typical agricultural cab. Before going to Noise Control Treatment (NCT) take to consideration of acoustic leakage can adversely affect operator comfort to a greater extent.

The cab is design of a metal structure with large enclosing panels of glass, polymers, and sheet metal. Also, it interference with several elements of machine which create gaps and openings. Identifying accurate leakage paths and deploying suitable counteraction results in tangible benefits such as silent cabin, improved passenger environment and ~~adds up~~additional intangible benefit as weather, dust.

This paper discusses the details about sources of acoustic leakages on off highway machine cab. In this paper, we used "Sound Intensity method" to identify the acoustic leakages in the cab. A sound signal is generated inside the cab with acoustic source and leakages were identified with help of 3D sound intensity probe.

Figure 1: Acoustic treatments used on a typical Off Highway cab.

Sources of Acoustic Leakages in Cab

The acoustic leaks in the cab can be due to gaps and openings in the structure joints, opening for pipes and cables, wiring harness, opening for HVAC, equipment attachments to cab etc. Design clearances for functionality like clearance at latch area, machine control mechanism like steering pedal and levers, dissimilar material combination like plastics and metal, seals and uneven connecting surfaces may also contribute to it.

Acoustic Leakages Detection Techniques

Use of fog machine is a traditional method to identify the leakages in the cab. Physical leakages can be identified using this method but it may not provide a representation, quantification and contribution in overall noise level.

Ultrasound leak detection is used to detect the leakages but has limitations in ability to categorize/rank the risk.

Noise level meter provides only noise level quantification, it may be difficult to identify the accurate location of the leak in critical areas. Limitation is Noise level was measured around the cab but sound waves may need to be manipulated to a specific direction or angle to improve detectability. Also, leakages hole size are not uniform.

Leakages detection is affected by numerous factors such as the flow, the size, shape, and configuration of leak orifice, temperature, and humidity of expelled air etc. Sound intensity technique can provide the detailed quantification of physical location and acoustic leakages accurately.

Sound Intensity

Sound intensity is a powerful technique that allows us to measure the flow of sound energy. Sound intensity is the power carried by sound waves per unit area. It is a vector quantity having magnitude and direction. It can be used for locating sources of sound leakages. Sound Intensity can be measured in any sound field so the test can be done in situ.

Sound intensity ($\vec{I}_{(t)}$) is product of sound pressure ($p(t)$) to particle velocity ($\vec{u}(t)$). Particle velocity is speed at which air molecules vibrate back and forth while transmitting a sound.

$$\vec{I}_{(t)} = p(t) \cdot \vec{u}(t) \qquad (1)$$

The vector product represents the flow of acoustic energy in a direction perpendicular to a surface. Measuring the particle velocity directly is not simple. So, the intensity is measured using the pressure gradient by linearized Euler equation. With this equation it is possible to measure the pressure gradient with two closely spaced microphones relate it to particle velocity.

$$\vec{I} = \frac{p_1 + p_2}{2}. \; -\frac{1}{\rho}\int_0^t \frac{p_1 - p_2}{\Delta r}\, dt \qquad (2)$$

As shown in Equation 2, the pressure gradient signal is integrated to get the particle velocity. The estimate of particle velocity is made at position in the center of the probe between two microphones. Pressure is also obtained at this center by average of two microphone signal.

Sound Intensity Test

Sound intensity system consists of probe and analyzer. The probe measures the pressure at two microphones spaced face to face with solid spacer as shown in Figure 2 and the analyzer calculates the sound intensity. This arrange found the better for frequency response and directivity. Different sizes of spacer are used depending on the frequency ranges requirements.

As pressure is a scalar quantity and the probe measures the pressure difference between the two microphones, it is critical to appropriately orient the probe in sound field. Intensity probe should be orthogonal to the surfaces on which the intensity mapping is to be done. This technique can be extended to triaxial intensity vector measurement using 4 microphones.

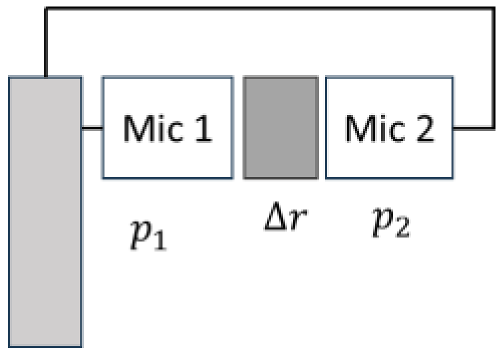

Figure 2. *Sound Intensity Probe with two microphones.*

A tetrahedron configuration probe with four microphones as shown in Figure 3 can measure the intensity in three directions. The Sound intensity vectors can be calculated along the X, Y, Z axis from sound pressure measurement p1(t), p2(t), p3(t) and p4(t) using Euler's equation.

$$I_x(t) = \frac{P_{x_1}(t) + P_{x_2 l} t}{2} \int \frac{p_{x_1}(t) - p_{x_2}(t)}{\rho \Delta r} \mathrm{d}t \qquad (3)$$

Where, ρ is the air density, Δr is the spacer distance between microphone considering the sphere.

Figure 3. 3D *Sound Intensity Probe*

Testing

This test was done on the off-highway cab. The fully assembled cab was used for this study. The cab was set up in hemi-anechoic room on hard floor isolated through air bellows. The Omni-directional sound source was used as a source to identify acoustic leakages. Sound source radiates the measurable uniform acoustic excitation inside the cab.

The Omni-directional sound source is kept at the operator ear location. Omni sound source generates a white noise in the frequency range from 50 Hz – 16 kHz. The white noise contains equal energy in each frequency. Sound inside the cab leaks through the holes, gaps and openings. These acoustic leakages are tracked outside the cab at a certain distance away from surface with 3D sound intensity probe.

Traditional sound intensity technique requires a virtual grid around the object, and it is required to measure along the normal to measuring surface to avoid distorted data due to probe orientation and distance variation. Sound pressure-based measurement as shown in Figure 4 around the cab surface uses discrete method in which one needs to divide the surface into smaller areas and measure the one discreate location for given period. This process is more time-consuming.

The 3D sound intensity probe and analyzer measure the sound intensity in in 3 directions. It consists of four phase-matched microphones in tetrahedral orientation in metal sphere of 30 mm diameter. 12 mm spacer distance used in between each microphone. This probe can measure the 3D intensity from 100 Hz- 4 kHz. 3D probe can operate at much fast speeds and can record the intensity in all 3 directions. It can work with more complex geometry as well. This is advantageous as cab acoustic leakages are on the complex surfaces due to the complex shape of the cab.

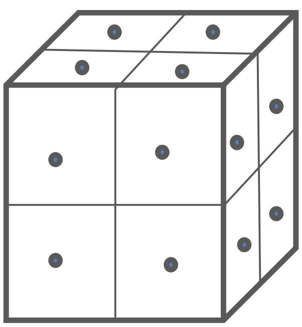

Fig 4. Discrete method for sound intensity

The probe needs to be moved along a direction normal to the surface in a straight line with constant speed over the scan path as shown in figure 5. Each surface of the cab is scanned by maintaining a constant distance from the cab surfaces. Total 5 surfaces were scanned for acoustic leakages individually. Sound source location and input energy is kept constant during each surface scan. Each surface is scanned 2-3 times to increase the points density as well as to ensure the results consistency.

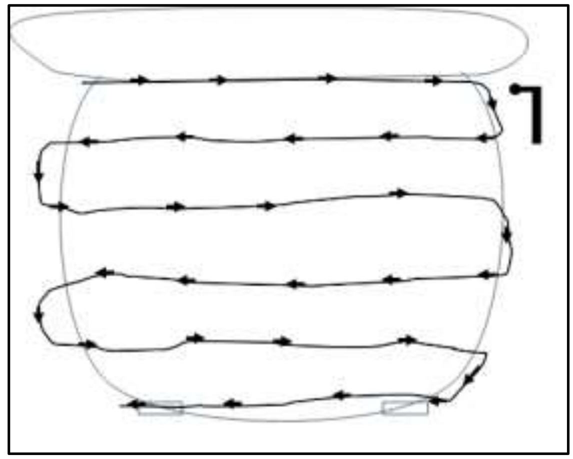

Fig 5. Scanning method for sound intensity with 3D Probe

Acoustic Leakages Identification

The data acquired by 3D probe is processed to calculate the intensity in each direction (X, Y and Z). Octave and spectral plots are obtained for each point. The resulting amplitude and direction is internally calculated to get the 3D intensity. leakages in the cab front side and corresponding maximum intensity octave plot is shown in figure 7a and 7b.

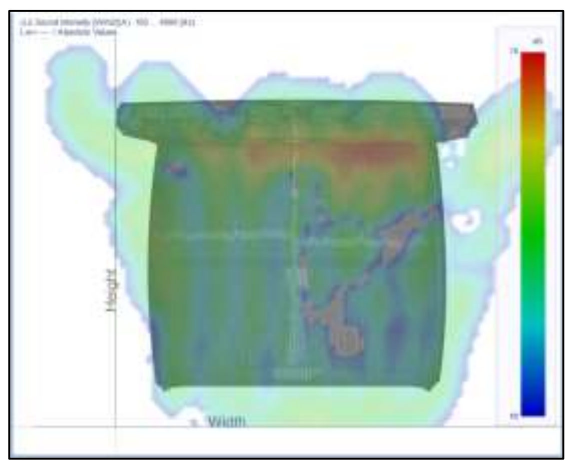

Fig 6. 3D Sound Intensity plot for Cab front Side shows the leakages.

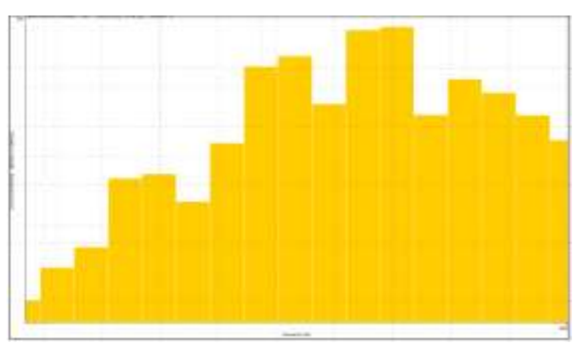

Fig 7a. Octave plots shown the 3D Sound Intensity plot for Cab front Side shows the leakages.

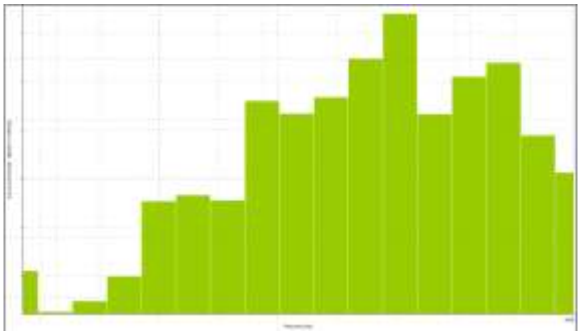

Fig 7b. Octave plots shown the 3D Sound Intensity plot for Cab front Side at point shows the leakages.

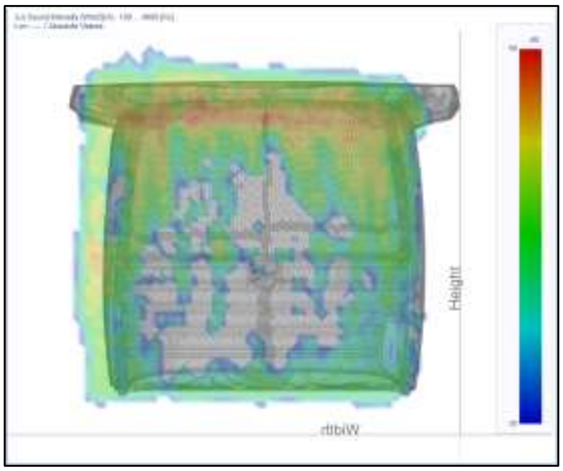

Fig 8. 3D Sound Intensity plot for Cab Rear front Side shows the leakages.

After calculation of the sound intensity with help of magnitude and vector direction leakages can be identified on the cab surface. These leakages are further validated subjectively. Maximum leakages are observed at cab front side surface, top side near the air duct and gap between top hood and frame as shown in fig.6. The leakages are also observed between the top hood and frame connecting the gap as shown in fig 8.

Conclusion

Summary/Conclusions

Sound Intensity technique was successfully used to identify the critical acoustic leakages from all surfaces of the cab. The critical paths and surfaces of the cab are identified based on the measurements. This information is useful to evaluate design solution to reduce noise inside the cab.

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Contact Information

Sachin Pawar
John Deere Technology Center India,
Tower XV, Cybercity, Magarpatta City,
Hadapsar, Pune 411 013, India
Office: +91-20-6648-1374
Email: PawarSachinM@JohnDeere.com

Acknowledgments

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Definitions/Abbreviations

NCT	Noise Control Treatment
HVAC	Heating, ventilation, and air conditioning.

Appendix

The Appendix is one-column. If you have an appendix in your document, you will need to insert a continuous page break and set the columns to one. If you do not have an appendix in your document, this paragraph can be ignored and the heading and section break deleted.