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THE DETERMINATION AND RANKING OF INTERIOR CABIN NOISE SOURCES VIA ADVANCED MATRIX MANIPULATION

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ABSTRACT

The noise perceived inside a vehicle is a combination of airborne noise from the main noise sources such as gearbox, tyres, or engine plus any structurally induced from vibrations at the drive train interface or road induced from the vehicle's progress along the road. Airborne noise is regularly studied using the author's Acoustic DNA technique, but structure borne analysis can be far more complex and time consuming. This paper examines a novel panel contribution technique called SPEA which provides a companion to acoustic DNA. This enables not only the structural component to be extracted but also the NVH package to be optimized accordingly. A description of the measurement procedure is outlined along with the necessary analysis stages. Example results are included together with the airborne / structural split. Further work includes a sound phonon simulation method for comprehensive NVH package analysis.

Keywords: *acoustic dna, sptf, galerkin, substitution, superposition*

1. INTRODUCTION

Noise levels perceived inside the cabin of a self-propelled motor vehicle are generated then transmitted from their source location via two fundamental processes. Either airborne from the surface of the source or structurally via their mechanical coupling to the vehicle body. The balance of airborne versus structure borne sound power entering the cabin depends on the complex nature of the vehicle's construction and its propulsion system. The cabin surface is where both airborne and structure borne components combine. Whence they radiate into the volume of the cabin to be received at the passenger ear position as sound waves which can be either pleasant, providing character or unwanted as noise.

Understanding which is airborne or structure borne traditionally involves considerable test activity. This paper describes a novel technique called Spatial Power Evolution Analysis (SPEA) which isolates the total radiated sound power from each cabin surface. When used in conjunction with Acoustic DNA [1], which calculates the airborne component, the structural contribution can be determined. From an NVH perspective this split is not mandatory, and this paper shows that SPEA can effectively optimize a treatment package for any operating condition of the vehicle, especially at high road speed.

2. METHOD OVERVIEW

The interior cabin surface is split into a Galerkin distribution according to the individual body sub-systems. For each sub-system an indicator microphone is juxtaposed to measure the local sound field during vehicle operation. Microphones are also placed at the drivers' and passengers' head positions; these are called receiver microphones. Two indicator microphone locations are shown on figure 1, for the windscreen and Instrument panel. In practice at least 40 microphones are required.

Figure 1. Example Locations of Indicator microphones.

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It is expected that during vehicle operation, the sound spectra recorded at each indicator microphone will contain a mixture of the effect of noise radiating from all the cabin surfaces, both airborne and structure borne and as such is of little practical use in identifying problematic cabin sources. This is called cross talk contamination.
To overcome this, SPEA uses a combination of source substitution and superposition together with a decontamination algorithm so that the radiated sound power of each cabin sub-system surface is mathematically isolated from its neighbours and its contribution to the overall sound pressure level spectrum at receiver microphones can be determined. An overview of the technique is shown on figure 2.

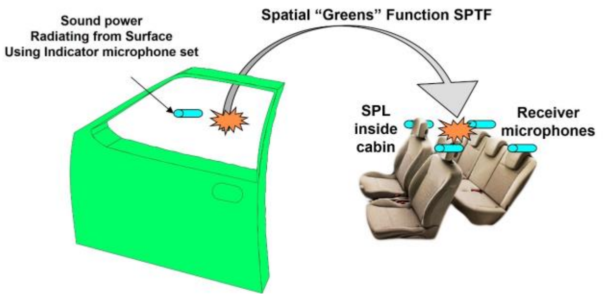

Figure 2. Overview of SPEA Methodology

To enable the decontamination algorithm to function a series of calibrated source substitution transfer functions are measured spatially using superposition techniques between each sub-system, and each of the indicator microphones and the receiver microphones to form a cross-transfer matrix. In each part of the matrix the spatial transfer function is calculated as a sound propagation transfer function (SPTF) or "Greens" function, using equation 1.

$$\text{SPTF} = \text{SWLx} - \text{SPL r} \tag{1}$$

Subsequently on road operating sound pressure spectral data is collected for all indicators and receiver microphones.

3. POSTPROCESSING

Real time third octave spectra are sampled from the digitally recorded time histories for both the operating and transfer function responses and imported into a server-based web application called "Genome" [2]. Subsequently, a bespoke decontamination algorithm adjusts each sub-system sound power so that the entire sound field inside the vehicle is recreated in as close to the measured SPL of each indicator microphone whilst maintaining the sub-system cross transfer function, measured during the substitution phase. The final cabin SPL is generated by manipulation of the sound powers and subsequent transfer to each receiver microphone at the driver and passenger head positions. Both measured and predicted SPL can then be compared and the contribution of each sub-system determined. SPEA was configured to operate from 200Hz to 10kHz to accommodate the effective working range of typical soft NVH trim.
Genome reduces the need for each team member to have a high-performance PC and creates useful team interaction throughout the project.
Genome provides a rapid solving environment after which the results can be displayed against road speed, under wide open throttle acceleration, as in figures 3 and 4 or as frequency spectra at any operating condition. Figure 3 shows good correlation between measured and predicted cabin overall dBA level whilst figure 4, displaying the highly sensitive "open articulation index %", only deviates from the measured value at 148 kph where a momentary event, inside the cabin, reduced the measured value. A key advantage of SPEA is that it can provide accurate predictions within the entire vehicle operating envelope as all the microphones are inside the cabin and not subject to extraneous excitation from the wind or changing exterior ambient conditions.

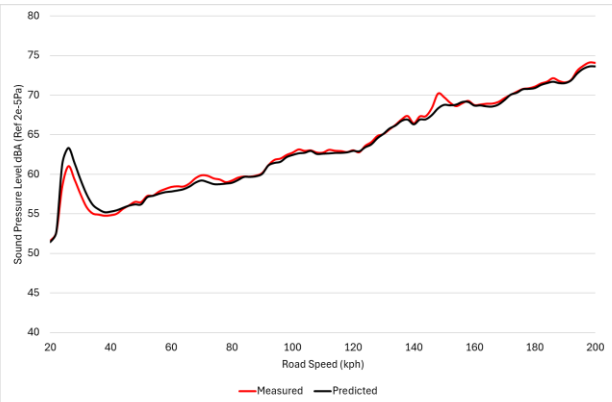

Figure 3. Measured v SPEA Predicted Cabin dBA v Road Speed

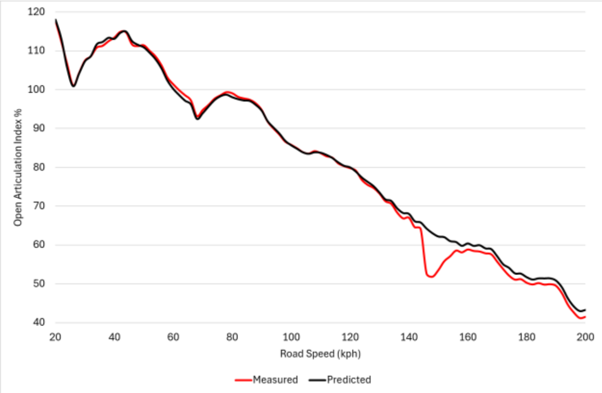

Figure 4. Measured v SPEA Predicted Cabin Open AI% v Road Speed

Investigation into the noise contribution was undertaken at all road speeds but a road speed of 198 kph was chosen as an example. The solver error, responding to the average difference between the measured indicator SPL and predicted SPL, can be displayed to allow the operator to establish this as a usable result, as shown in figure 5 and is typically around 1dB.

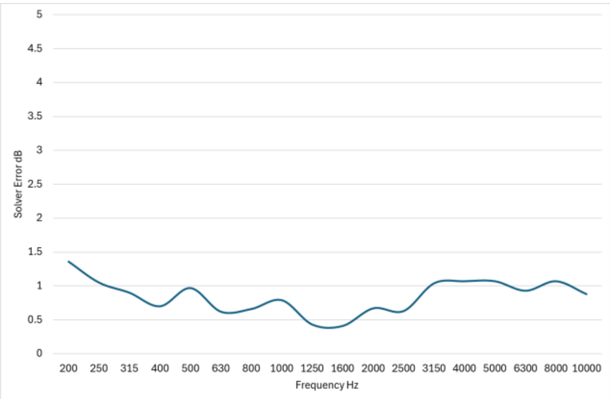

Figure 5. Display of solver error (198 kph road Speed).

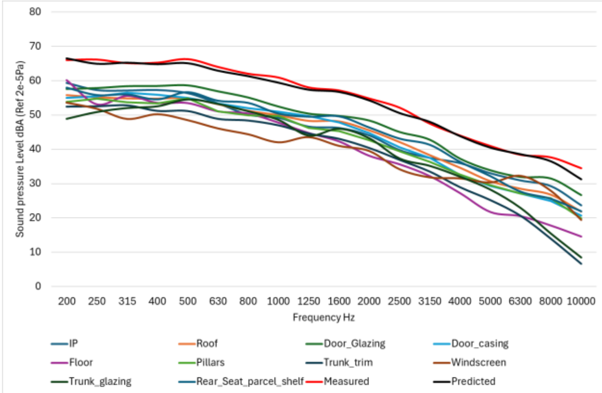

Figure 6. Measured v SPEA Predicted Cabin Level and Contributions (198 kph road Speed)

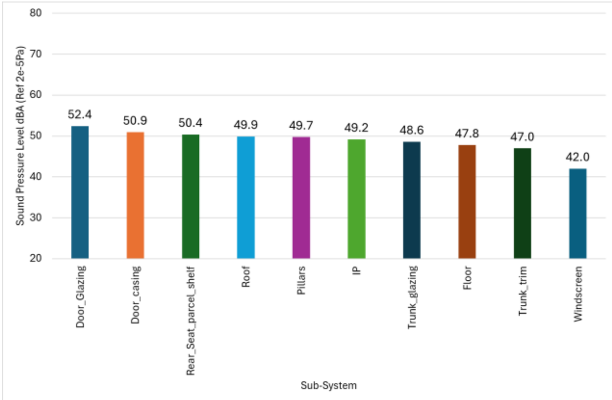

Figure 7. Contribution Ranking at 1kHz (198kph road Speed)

For clarity of charting each group of sub-systems is integrated. So that the four individual door glazing sub-systems is now represented as a single group. Figure 6 shows the spectral contribution of each group, and figure 7 shows a pareto analysis at 1kHz. As expected, the door glazing dominates at 198 kph.

Genome includes an optimizer routine which enables the user to identify potential vehicle improvements to reach a given cabin noise level target. Activating the optimizer involves choosing a road speed together with a required improvement, either as AI% or dBA, shown in figure 8.

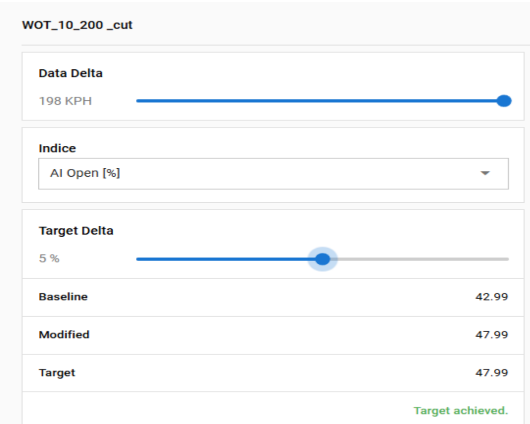

Figure 8. Initiating the SPEA optimizer function

Next the maximum acoustic performance changes allowed for each group are chosen, in this case a 5dB reduction in radiated sound power. Figure 9 shows the result of the optimizer where the door glazing would require a 4.3dB reduction in sound power combined with a 2.2 dB from the rear seat / parcel shelf and around 1.4 from the IP, Roof and door casings to achieve the 5% improvement in open articulation index

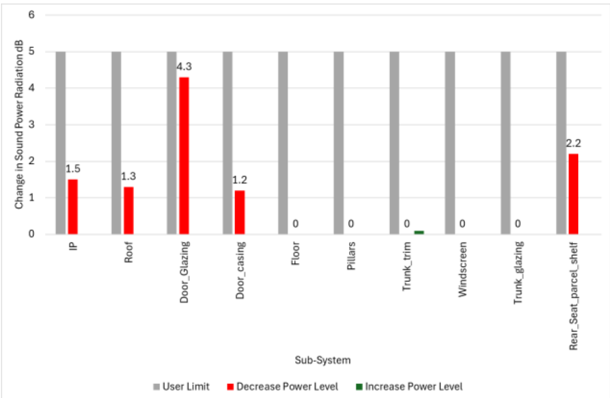

Figure 9. Results from SPEA optimizer function

Whilst at 198 kph wind noise dominated the cabin noise spectrum via the door glazing at lower speeds it is interesting to examine the difference between the airborne contribution from the power unit and tyres, which radiate into the sound field outside the cabin to that radiated sound power from each interior group. The Acoustic DNA method [1] for airborne source contributions is limited to 120 kph due to wind interference with the microphones above that speed. Comparing the difference, in sub-system radiated sound power at 120 kph between vehicle airborne source contributions and total sub-system radiated sound power gives an approximation of the structural panel effect and any extraneous wind noise at 120 kph. This is called the residual sound power and figure 10 shows this residual for the rear door glass.

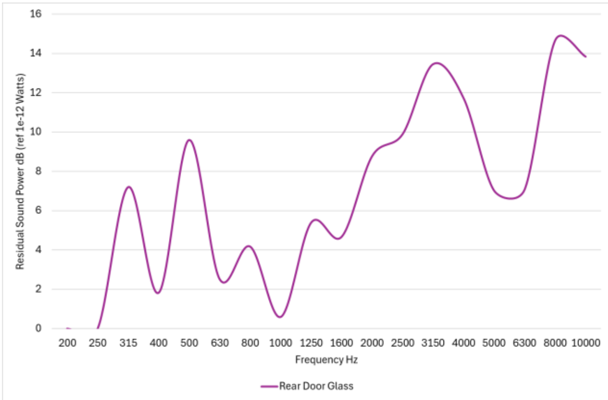

Figure 10. Residual Radiating Sound Power for Rear Door glass.

The use of residual radiating sound power calculations has suggested the need for a fundamental switch from using purely airborne noise techniques for vehicle optimization to those that include structural and wind noise effects. This is most noticeable for EV's where the power train radiated noise is significantly lower than the tyres or the contribution of the vehicle simply vibrating as it moves along the road surface – called "shell" noise. Figure 11 shows the significant difference between measured cabin SPL, SPEA predicted and airborne only using the Acoustic DNA method, for a large EV SUV at 120 kph.

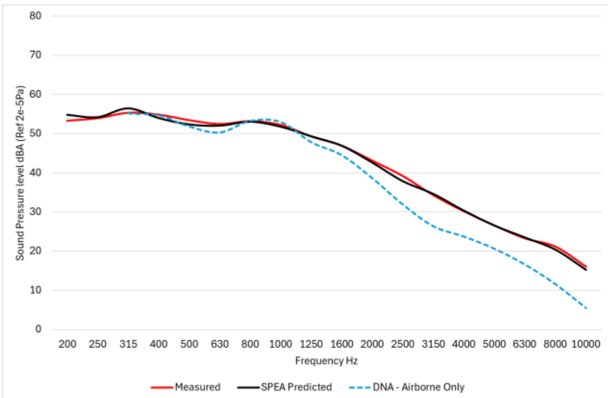

Figure 11. SPEA Predicted v Airborne Only and Measured Cabin Spectra.

The consequence of EV's acoustic balance between airborne and structure plus wind noise has a profound effect on future simulation modelling techniques.

4. SIMULATION USING SOUND PHONONS

The technical papers [3] and [4] describe the use of sound phonons in an efficient GUI modelling regime that simulates airborne noise transmission. With EV's now generating a considerable amount of shell noise it was necessary to revisit the use of sound phonons and modify the GUI accordingly. Traditional techniques such as statistical energy analysis (SEA) can incorporate airborne, structural excitation and wind noise via CFD computation. However, the latter requires significant computational input. From a trim and hardware supplier perspective the key reason for simulation is to determine the effect of changes or additions to the NVH package within a short time frame. The SPEA technique can provide a benchmark dataset for shell noise to be examined and optimized.
Incorporating the SPEA dataset into a sound phonon model requires the use of vibroacoustic reciprocal excitation (VARE) where the model is moved into a fully reverberant chamber and a suitably adjusted excitation source creates an even diffuse sound field around the vehicle cabin model.
Each sub-system of the vehicle model has its transmission loss adjusted so that the interior radiating sound power associated with the exterior diffuse sound field represents that predicted during the SPEA analysis. Figure 12 shows an EV SUV placed in its reverberant chamber, with figure 13 showing the interior. In practice it is not necessary to remove the body work from the engine bay, wheels etc. only to switch them to acoustically transparent so that the diffuse sound field encompasses the main cabin body shell.

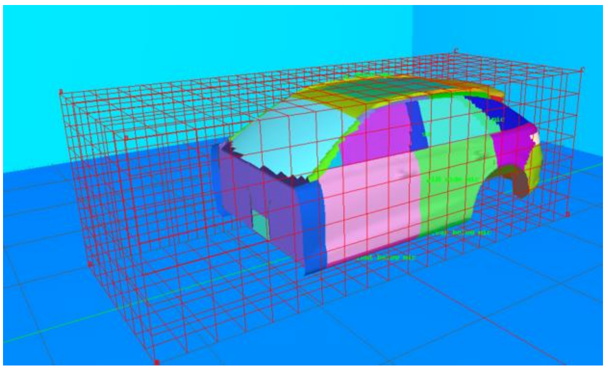

Figure 12. EV SUV simulation in a reverberant chamber.

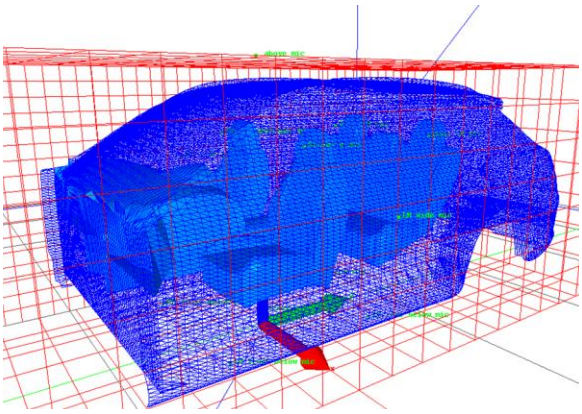

Figure 13. The Interior of the EV SUV simulation in a reverberant chamber.

With the sound phonon model in this novel VARE condition, the cabin noise spectra was compared to the SPEA prediction and measured at 120 kph and this is shown on figure 14 and table 1.

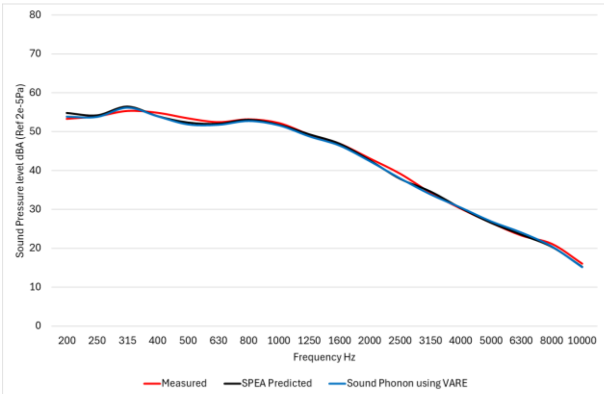

Figure 14. SPEA Predicted v Sound Phonon and Measured Cabin Spectra (120 kph road speed).

Table 1. Comparison of dBA and AI for SPEA Predicted v Airborne Only plus Sound Phonon and Measured Cabin Spectra (120 kph road speed).

120kph Cruising	dBA	Ai%
Measured	63.1	78.4
SPEA Predicted	63.2	79.3
Sound Phonon VARE	62.9	79.9
Airborne only	63.8	82.7

Subsequently any sub-system of the model or the cabin interior trim can be modified and its effect determined. The only proviso being that any modification to the NVH on the cabin surfaces be "limp" in nature so that it does not significantly alter the structural integrity of the cabin.

5. CONCLUSIONS

This paper has briefly described the SPEA technique which enables the test evaluation of the combined airborne, structure borne and wind noise contributions radiating into the vehicle cabin. An example of the accuracy of the method has been provided, from the authors comprehensive customer-based portfolio, along with a description of the web-based optimizer function. The nature of noise inside modern EV's has been discussed and the increased need for the SPEA methodology justified accordingly.
With regards to subsequent modelling simulation the sound phonon method has been augmented with vibroacoustic reciprocal techniques so that time efficient NVH optimization can be performed.

6. DEFINITIONS / ABBREVIATIONS

EV = electrical vehicle
OEM = Original Equipment Manufacturer
SPL = Sound Pressure Level
SWL = Sound Power Level (x – source, r - receiver)
NVH = Noise Vibration and Harshness.
SPTF = Sound Propagation Transfer Function (SWL-SPL)
CAD = Computer Aided Design
DAQ = Data Acquisition System
SEA = Statistical Energy Analysis
AI% = Open Articulation index
CFD = Computational Fluid Dynamics
VARE = vibroacoustic reciprocal excitation.

7. REFERENCES

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