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Analysis of Performance Variances in Production Vehicles Using Digital Twins

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ABSTRACT

Audio systems in production vehicles are known to exhibit vehicle to vehicle performance variance [1]. A comparison study eliminated measurement uncertainty [2] by utilizing a digital twin [3] method where only one attribute is modified between comparisons. Utilizing loudspeaker drivers from within manufacturing tolerance, system comparisons were made with loudspeakers that have reduced or increased sensitivity. The impact of a missing gasket was analyzed as well.

1 Introduction

Premium audio systems for production vehicles were first introduced in the 1980s and since that time it had been generally accepted that duplicate audio systems in duplicate production vehicles will all effectively sound the same as their reference system counterpart. While that conjecture was generally accepted it was known to be false but rarely admonished. During the AES 48th Automotive Audio Conference there was an interesting workshop discussion, Automotive Audio Workshop: Audio Quality in Production and Long-term [4]. A panel of industry experts and the audience discussed their observations and experience related to audio system issues and variance in production vehicles. The issue was recognized as prevalent and pressing with participants from vehicle manufacturers as well as audio system suppliers acknowledging that they have at times been requested by their company's quality conformance group to address performance and quality related issues for production released vehicles.

1.1 Performance Quality

When customers complain to their auto dealer about the quality of the audio system in their vehicle, service technicians follow procedures to analyze and resolve the complaint. But the lack of robust audio system and acoustics diagnostics process that measures and compares system performance against known metrics leads to a practice of replacing components to see if a complaint or problem is alleviated. With warranty claimed audio hardware returns in excess of 68% having No-Trouble-Found (NTF) there is motivation to reduce NTF warranty costs [6].

1.2 Perception of Loudspeaker Variants

Briefly, performance tolerance metrics at the audio system level do not exist for vehicles. Deeper understanding of the perception of variants is required before metrics for system characteristics and allowable tolerance can be defined. That necessitates the need for a study to compare the impact of how system performance variance is influenced by traditional component production and manufacturing variance.

1.3 Single Component Substitution with Single Effect

When studying the effect on the full system when samples of loudspeakers with slightly different but allowable production tolerances are compared, the simple act of substituting a single loudspeaker may introduce overlooked changes not attributable to the device parameter differences. For example, removing the door trim, disconnecting a loudspeaker, replacing the loudspeaker, connection and door trim can perturb the system in an unexpected manner.

The Digital Twin method has been applied successfully over the past few years at major vehicle manufacturers as a Virtual Product Development method for automotive audio [7]. This method allows complete development of vehicle audio systems in a fully digital domain, relieving the requirement for prototype vehicles in the early stages of system development. With an uncanny similitude between Digital Twin and the real vehicle, resource requirements for development time and cost are reduced considerably, impacting time to market. For this study, utilizing the Digital Twin methodology allows the substitution of a single factor without disturbing any other attributes of the system.

2 Background: Typical Audio System Development Process

The Digital Twin system is developed using the same protocols as when defining and developing an audio system for OEM vehicles. The general protocol is as follows:

- Choose performance goals. Typically based on vehicle class with reference to subjective preference ratings. For example, Luxury brand, Branded, Premium etc.
- Define architecture required to achieve performance goals with focus on loudspeaker types and locations and necessary amplification and DSP.
- Choose components required to achieve performance goals.
- Assemble and tune the reference system using objective measurements and subjective evaluations.

The localized sound power technique as described by Geddes and Blind [8] is a tool to balance the frequency response and is still used in general practice. The general spectral target curve for full system balance (FSB) in the driver seat as seen in Figure 1, typically has a low frequency boost, gentle slope to the Mid-High and somewhat flat through to high frequency. This target spectral shape has remained quite constant throughout the years.

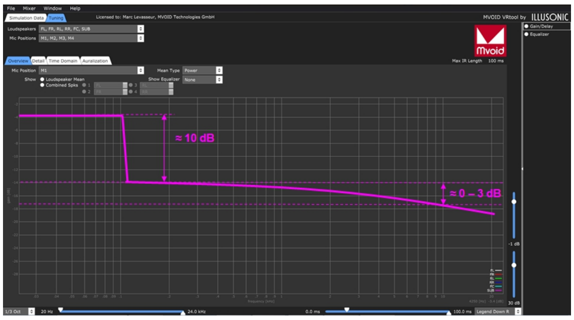

Figure 1. Example FSB Frequency Response.

- The process to achieve an acceptable performance curve includes equalizing each channel successively and alternating adjustments with subjective listening. Eventually and after agreement from stakeholders the reference system is agreed to meet objectives and equalization and DSP settings are frozen.
- Receive sign-off from stakeholders.
- Create document package that include architecture, component drawings, quality documents etc.
- Deliver document package to OEM customer as requested.

2.1 Audio System Specifications for the Vehicle Industry

The document package created at the end of the system development procedures do not include what could be considered an appropriate and comprehensive system specification. Most importantly, what is missing is a system level specification that can be used to verify if a system conforms to some norm with specific data metric for acoustic performance. Further, there is no detail or method to quantify metrics of the reference system that can be used to quantify if a production system conforms within some tolerance of the reference system. The general practice is to deliver customer specifications for components only. For example, loudspeakers include all aspects of details that describe the mechanical and acoustical attributes along with design verification, production validation method and requirements and finally, manufacturing tolerances and transducer end-of-line test attributes that identifies allowable tolerances of characteristics.

In summary, there is no industry standard for a vehicle audio system specification that includes objective data metrics or method of a robust measurement process. For that matter, the authors are not aware of any comprehensive corporate specification for audio system performance in vehicles. The lack of a system level specification impacts the ability to develop a useful vehicle production end-of-line test or service center diagnostic for vehicle audio systems.

2.2 Measurement Uncertainty

Measuring performance attributes of vehicle audio systems multiple times in the same vehicle can lead to varying results due to the complexity of the acquisition process [2]. Comparing different samples of real loudspeakers in real vehicles is compromised by physical perturbation as loudspeakers are installed and replaced. Even disruption of door panels can lead to performance variance not attributable to the loudspeakers.

3 Digital Twin Benchmark Methodology

The Digital Twins method is mature and robust, and used successfully in highly complex systems where assembling and testing hardware is not feasible. The Digital Twin method eliminates measurement uncertainty by allowing only a single difference to be compared at any one time. This study follows the practice for modeling audio systems in vehicles based on an extension of "Virtual Systems Engineering in Automotive Audio" [7].

3.1 Audio System Architecture

A typical SUV with a ten channel, ten loudspeaker audio system (4 door woofers and four door mid-highs, center midrange and trunk subwoofer) was studied. The audio system is based on an actual SUV variant with performance preference expectations typical for a branded system.

3.2 Digital Twin Model

The Digital Twin model includes all aspects of the vehicle that impact acoustic performance. Simulation and analysis are used to progressively develop the full model. Starting with the transducer electro-magnetics, structural dynamics and (air-borne) acoustics and proceeding through additive complexity of transducers in enclosures, enclosures in "room" as a system, tuning the system and then finally, the full system acoustics are auralized for listening via headphones.

Careful attention is addressed so that finally all pertinent details are included. A proper mesh must be generated so that an accurate acoustic analysis and sound pressure distribution as shown in Figure 2 can be carried out.

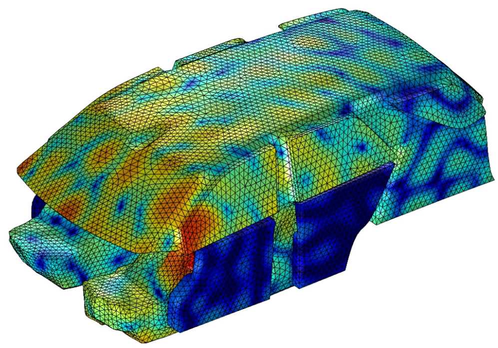

Figure 2. Finite Element Mesh and Sound Pressure Distribution.

3.3Data Acquisition

The acquisition of loudspeaker performance characteristics via the Digital Twin utilizes a version of a swept sine technique to capture the impulse response. This feature is built into an advanced system capable of measurement, tuning and auralization [9]. Multiple acquisitions, one for each microphone receiver can be acquired simultaneously and stored for any type of post-processing analysis. Figure 3 shows an image with spheres representing each microphone in a six-microphone array in each seat, total of 24 microphones for which complex data is acquired simultaneously.

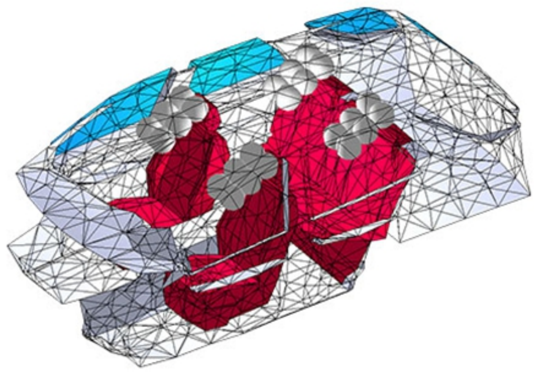

Figure 3. Six-microphone Array in Each Seat.

Modeling the acoustics requires a hybrid approach that utilizes a unique splicing technique that correctly captures accurate data, accounting for frequency vs. wavelength in the acoustic space. This is done by merging FEA analysis of low to mid frequencies and time domain based geometric analysis for the mid to high frequencies as depicted in Figure 4.

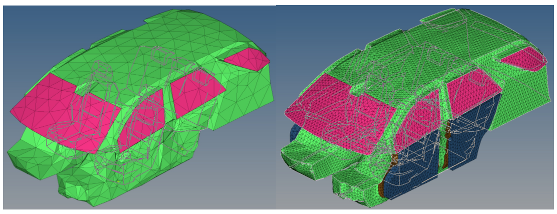

Figure 4. Simulation Meshes for Low to Mid to High Frequencies by Means of Geometrical Acoustics (left) and FEA (right).

3.4Virtual Tuning

After all data for each loudspeaker is acquired the Digital Twin tuning process can begin. The software tool provides an acquisition tool fully integrated with the measurement environment, allowing analysis and adjustment in both the frequency and time domains. A screen capture of the GUI is shown in Figure 5.

Figure 5. GUI of Software Tool.

To view or hide any specific data, toggles are provided in the GUI. Multiple tabs allow working between: Measurement, Overview, Detail, Time Domain and Auralization. All aspects of the acoustic tuning are managed in the tool, from tuning individual loudspeaker delays and gain, to equalizing frequency response amplitude of individual channels and analyzing how channels sum together acoustically. Comprehensive details can be studied, for example for any single microphone or combination with any combination of loudspeakers. Or, it is possible to review between driver seat vs. co-driver or rear seats data with a single click.

4 Loudspeaker Production Variance

To explore how loudspeaker production variance affects the system performance, two variants from the mean of the loudspeaker's production capability were developed for each of the Mid-High and Woofer. One variant at a higher sensitivity and one variant at a lower sensitivity. Variance values were chosen to be well within normal production tolerance of sub-components as shown in and listed in Table 1.

Dust Cap Mass	± 10%
Surround Stiffness	± 15%
Cone Mass	± 10%
Spider Stiffness	± 10%
Voice-coil Mass	± 10%
Voice-coil R_e	± 10%
Adhesives Mass	± 15%
Magnetic Gap flux	± 10%

Table 1. Typical Component Variance.

4.155mm Mid-High Loudspeaker

As components and the assembly deviate from the production mean the changes in mass, DCR, compliance and Bl affect Q*es,* Q*ms* and Q*ts* and sensitivity with influences on frequency response and impedance.

The parameters for the 55mm Mid-High:

Mid-High			
55mm	**Reference**	**Low**	**High**
SPL [dB]	85.6	83.5	87.7
Mms kg	0.00112	0.00140	0.00105
Cms m/N	0.000444	0.000495	0.000370
Fs Hz	225.6	191.2	255.2
BL Tm	2.85	2.80	3.10
DCR Ω	3.20	3.20	2.90
Q_{es}	0.63	0.69	0.51
Q_{ms}	3.08	6.00	2.50
Q_{ts}	0.52	0.62	0.42

Table 2. Component Variance for Mid-High.

The simulated (based on a lumped parameter model) graphs for the 55mm Mid-Highs are shown as on a 2π infinite baffle in Figure 6, normalized vs. the reference in Figure 7 and impedance in Figure 8.

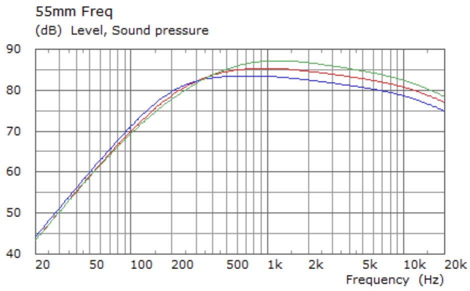

Figure 6. Mid-High Response Comparisons.

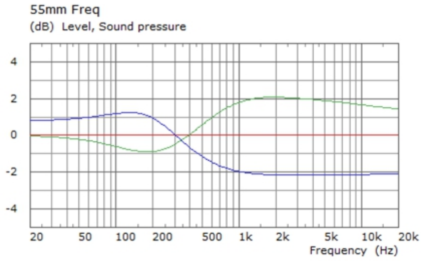

Figure 7. Mid-High Normalized Response.

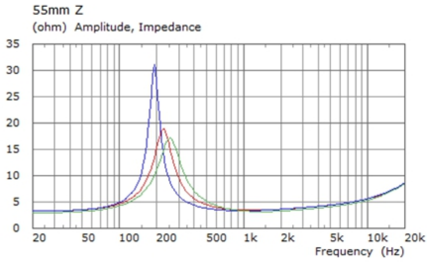

Figure 8. Mid-High Impedance Comparisons.

4.2165mm Woofer

165mm	Reference	Low	High
SPL [dB]	89.70	87.60	91.66
Mms kg	0.013110	0.013900	0.012500
Cms m/N	0.000366	0.000476	0.000290
Fs Hz	72.63	61.86	83.61
BL Tm	4.14	3.80	4.20
DCR Ω	1.85	2.03	1.57
Q_{es}	0.65	0.76	0.58
Q_{ms}	4.43	10.00	2.80
Q_{ts}	0.56	0.71	0.48

Table 3. Component Variance for Woofer.

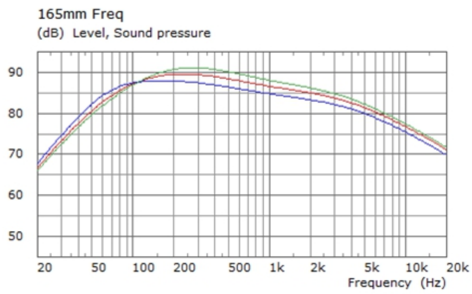

Figure 9. Woofer Response Comparisons.

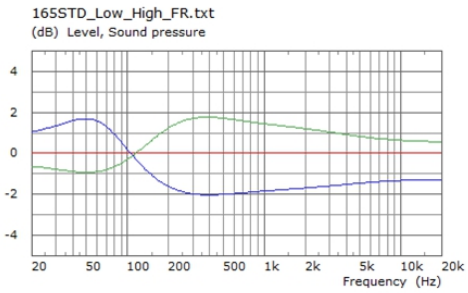

Figure 10. Woofer Normalized Response.

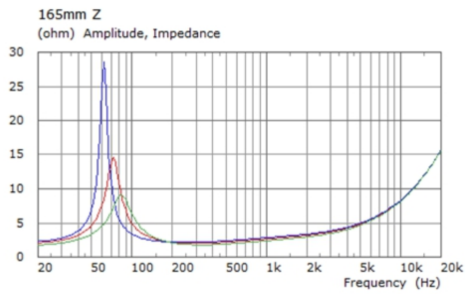

Figure 11. Woofer Impedance.

5 Analysis on Loudspeaker Variance on the System

The Digital Twin SUV audio system was developed and tuned by following the process outlined in section [2]. Four Scenarios were reviewed. The first being a reference system with reference tuning applied to create an equalization file that was used on each of the other Scenarios.

5.1 Scenario 1: Reference System

The reference system was first assembled with loudspeakers that have performance metrics and characteristics that are on the mean of their loudspeaker manufacturing tolerance. DSP equalization is applied utilizing bi-quads for delay, cross-over, notch and peak filters.

The driver seat localized sound power frequency response is shown in Figure 12.

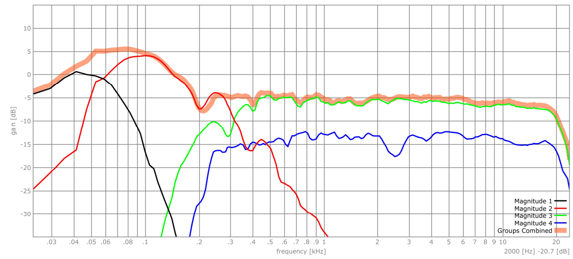

Figure 12. Scenario 1 Reference System.

5.2 Scenario 2: High Sensitivity Left Front Mid-High

Scenario 2 substitutes the mid-high left front loudspeaker with higher sensitivity of 87.7dB vs. the reference of 85.6dB is shown for the full system with localized sound power driver seat in Figure 13.

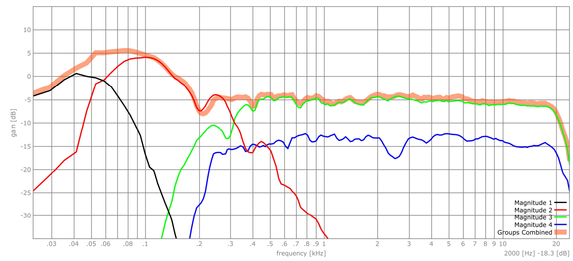

Figure 13. Scenario 2 High Sensitivity FLM.

In comparison of the frequency response of the higher sensitivity LF mid-high shows a modest +2dB above 1kHz as shown in Figure 14 with a small reduction of voltage sensitivity below ~300Hz.

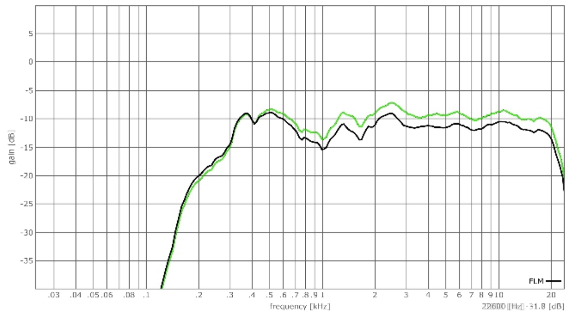

Figure 14. Green=LF Mid +2dB Sens vs. Blk=Ref.

5.3 Scenario 3: Reduced Sensitivity Right Front Mid-High

Scenario 3 substitutes the right front mid-high with lower sensitivity of 83.5dB vs. the reference of 85.6dB as shown for the full system with localized sound power driver seat in Figure 15.

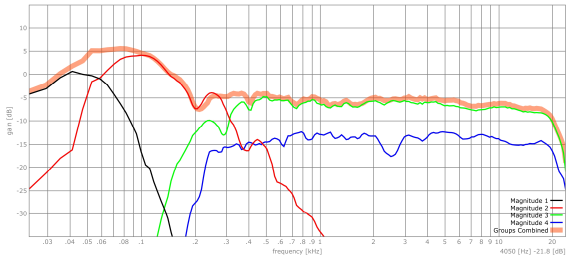

Figure 15. Scenario 3 Reduced Sensitivity FRM.

The reduced sensitivity mid-high frequency response shown in Figure 16 exhibits ~2dB variance above ~300Hz vs. the reference.

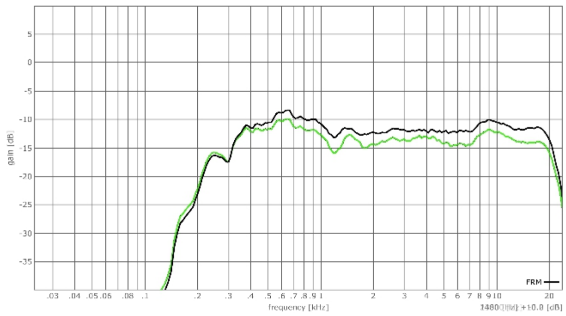

Figure 16. Green=RF Mid +2dB Sens vs. Blk=Ref.

5.4 Scenario 4: Missing Gaskets from All Woofers

Scenario 4 exemplifies a system where the Woofers are missing gaskets between the loudspeaker frame and sheet metal door mounting, a not uncommon quality failure mode. This full system frequency response with Woofers missing their gaskets exhibits a clear difference in the 125Hz to 300Hz region with a reduction of ~5dB to 6dB as can be seen in Figure 17.

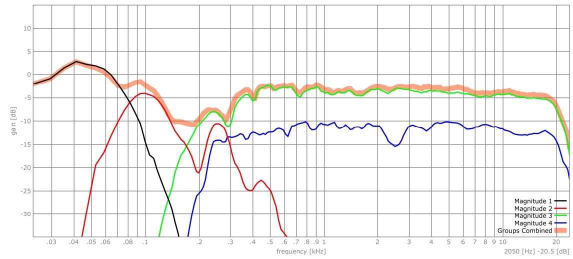

Figure 17. Scenario 4: Missing Woofer Gaskets.

The following figures compare same location Woofers for the reference system vs. the missing gasket.

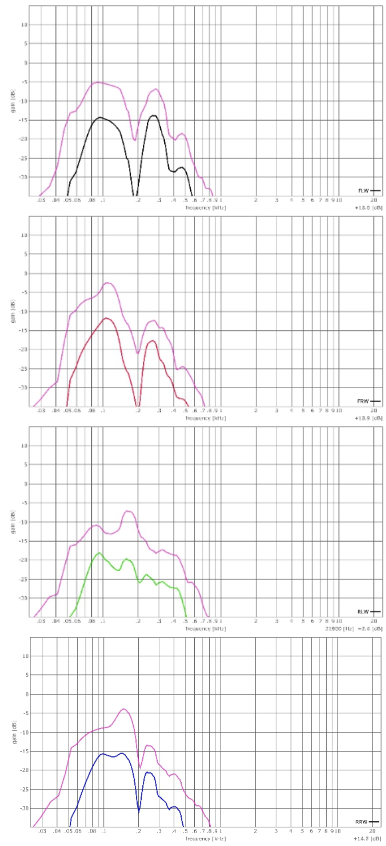

Figure 18. Reference system (magenta) vs. the missing gasket.

6 Conclusions

Analysis of performance variances in production vehicles is a complex problem compounded by measurement uncertainty in real vehicles that obfuscates variance as well as the true root cause of variance. Utilizing a Virtual Product Development Digital Twin where only a single desired change was implemented at any one time, variables were analyzed.

This study has demonstrated that small variances in loudspeaker driver parameters, that are still within manufacturing tolerance, cause differences in system performance that can be measured objectively in comparison to a reference system.

However, analyzing an installation aberration of missing Woofer gaskets demonstrated a significant impact, down-grading preference in a manner that may initiate a warranty complaint.

Loudspeakers with parameters that perform near the limits of manufacturing tolerance affect the overall system performance. Future work is related to a calibration equalization applied to rectify loudspeakers to perform as a duplicate of the reference system. This topic will be presented in the near future.

References

[1] S. Hutt, “Audio System Variance in Production Vehicles”, AES 48th International Conference Automotive Audio, (2012).

[2] C. J. Struck, “Measurement Uncertainty and its Application to Acoustical Standards”, Audio Engineering Society, (2017).

[3] E. H. Glaessgen, D. S. Stargel, “The digital twin paradigm for future NASA and US Air Force vehicles”, American Institute of Aeronautics and Astronautics, (2012).

[4] Workshop, “Audio Quality in Production and Long-term”, Audio Engineering Society, (2012).

[5] M. Kleiner, B.-I. Dalenbäck, P. Svensson, “Auralization – An Overview”, Audio Engineering Society, (1991).

[6] D. Douthit, M. Flach, V. Agarwal, “A Returning Problem: Reducing the Quantity and Cost of Product Returns in Consumer Electronics”, Accenture Report, (2011)

[7] A. J. Svobodnik, “Virtual Systems Engineering in Automotive Audio”, Audio Engineering Society, (2011).

[8] E. Geddes, H. Blind, “The Localized Sound Power Method”, Audio Engineering Society, (1984).

[9] A. J. Svobodnik, “A Fully Digital CAE-based Multi-disciplinary Development Environment for Virtual Sound Design of EVs/HEVs”, Carhs: Automotive CAE Grand Challenge 2018, (2018).