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An FFT-iFFT combination based transfer function approach to improve effectiveness of vehicle in-cab sound quality assessment.

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Summary

Customer comfort related to a pleasing sound quality is key-towards achieving a competitive edge, specifically in the automotive industry today. This is more critical for vehicles falling into passenger car segments, specifically in the M1, M2 and M3 vehicle categories. With more focus towards NVH, it is important to also consider the "design for NVH" aspect in addition to fulfilling the primary requirements of performance, durability and legislative needs. With increasing focus towards electrification, the focus is also shifting towards improving the overall vehicle sound quality, be it, powertrain noise, operational sounds (such as door closure), or even improving the sound quality of the car-multimedia systems.

The study conducted in this paper, details how in cab sound quality can be front-loaded much earlier into the design. This has been illustrated with use of a simplified FFT-iFFT based approach to improve sound quality of vehicle multimedia systems. The audio quality tuning for car-multimedia system requires engineers to tune the hardware/amplifiers through rigorous audio jury tests within the cabin for different audio filter (Equalizer) settings. There is a huge dependency on vehicle cabin, as the cabin acoustic properties significantly affects the sound quality perception for a specific car multimedia audio filter settings. In this study, a unique method has been developed to eliminate the dependency of vehicle cabin properties in order to simulate the perception under laboratory conditions, with minimal dependency on vehicle availability. This paper also talks about how the simulated audio settings can then be used for conducting controlled sound quality jury testing in order to arrive at the most ideal filter settings for a specific vehicle design much earlier in the development phase.

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1. Introduction

Automotive Audio System consists of the equipment installed in a car or other vehicle to provide in-car entertainment and information. It could consist of FM radios to modern smartphone integration systems like Android Auto and Apple Car Play. Modern designs of the audio system also include navigation systems, voice recognition, engine noise generators and active sound control systems. Nowadays, most OEM provide custom designed multimedia system pre-installed in the vehicle. These are tuned to the vehicle depending on the acoustic properties of cabin, speakers and target consumer segment.

The typical layout of a 5-channel car audio system is shown in figure 1. It consists of a head unit, amplifier, 4 door speakers, a subwoofer and connecting wires. The head unit of the system is fixed on the dashboard and is powered by the vehicle battery system. It receives all user inputs and sends pre-amplified audio signals to the amplifier. The audio system power amplifier is usually placed is in the boot or trunk with power supplied from the car battery with related power electronics to control power demands and surges.

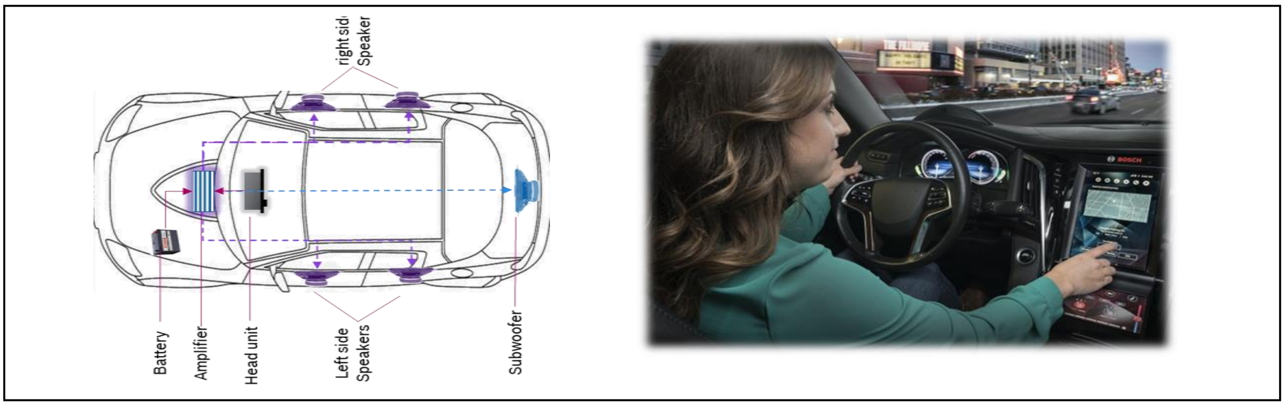

Figure 1. Typical Car Multimedia Architecture

The power amplifier amplifies the signals from the head unit and sends them to the speakers of the audio system. The speakers are placed on the doors with the subwoofer located in the trunk with its own dedicated enclosure. Audio systems with up to 32 speakers are also available now.

2. Overview

A car multimedia system requires specific tuning for every individual application (car cabin design/speaker configuration). This is because every vehicle cabin has specific acoustic properties /cabin modes or mode shapes [1]. The sound perceived inside a vehicle cabin plays an important role in deciding the acceptance of an automotive audio system. This perceived interior audio response is completely different from one which is heard in a free field or a headset. Hence proper tuning of the vehicle audio system is paramount in the design phase of the automotive audio system. The difference in the audio characteristics arises due to specific acoustic properties of each cabin and related acoustic transfer functions [1]. The transfer function is typically a function of the geometry of BIW, acoustic material used and also the number of people sitting inside.

Such strong acoustic modes generated in localized regions within the cabin completely alters the response of sound inside the vehicle. For example, consider a car multimedia system playing an audio file which generates a flat amplifier output response as shown in below figure 2.

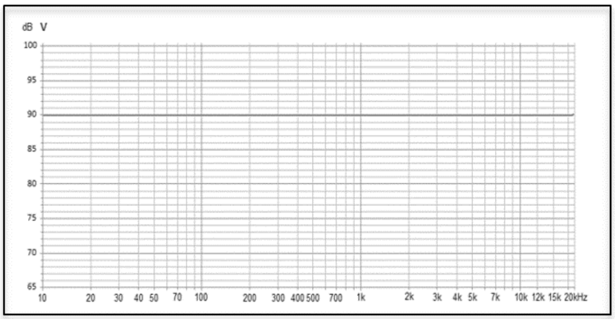

Figure 2. Flat amplifier input

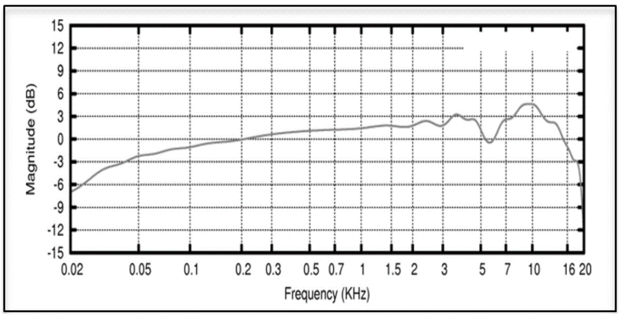

Figure 3. Perceived In-cabin Audio response

This is similar to a perceived audio response in a pure free field with a unity directivity factor. But the presence of varying acoustic modes inside the cabin alters the frequency response as shown in figure 3.

2.1. Typical Vehicle Multimedia Audio Tuning

As of today, once the multimedia head unit hardware and software design are finalized, the standard filter equalizer (EQ) settings for the systems are built in such as, Flat, Rock, Jazz, Pop etc. However, the standard settings can hugely get influenced due to vehicle cabin as indicated earlier. This can deteriorate or change the subjective sound quality at a specific intended factory settings. This calls for subjective tuning of the EQ settings by listening experts inside the actual vehicle cabin. The process however has some drawbacks:

- Time-consumed is high as experts spend hours tuning the system to produce the audio response they find ideal.
- Requires actual vehicle cabin until settings freeze. This dependency may be critical specifically during jury testing.
- Availability of all Juries (OEM/supplier) at time of tests can be a challenge.
- Finalizing EQ settings is based on trial and error basis and tests have to be done at all hearing locations (Driver ear, Passenger, Rear passenger etc.).

2.2. Proposed Solution

The proposed solution (shown in figure 4) focuses on simulating the perceived in-cabin audio response in a laboratory environment. This enables the engineer to make changes to the audio response rapidly in the lab and jury evaluations can be conducted in the laboratory environment.

The study conducted in this paper, details how the car multimedia sound quality can be front-loaded into the design of vehicle audio system. The method has ability to rapidly modify the audio responses according to the jury ratings with minimal dependency on the actual vehicle cabin. Only the final jury accepted EQ setting needs to be applied and validated for actual vehicle audio system.

2.3. Description of Approach

This method developed for the reproduction of in-cabin audio response relies on deriving a single filter (using an FFT-iFFT combination method) which replicates the in-cabin audio characteristics. This filter is a transfer function relating the audio file to the in-cabin frequency response. The advantage of this method is, you could use an existing cabin. Also as compared to the usual process of deriving acoustic transfer function [2] using a volume velocity source(VVS) or speaker, the method takes advantage of prototyped/final hardware architecture (speakers, amplifiers) and derives transfer function which is dependent on electrical characteristic voltage output of amplifier and measured acoustic response at ear locations. This puts minimal dependency on expensive sound sources. The derivation of such a filter is described below:

2.3.1. Filter Design

A test audio file (sine sweep (from 50 Hz to 20KHz.) is played through the audio system of the vehicle. The response of the cabin is recorded at specific locations in the cabin using a microphone. Consider this as $X2 + iY_2$ and simultaneously the electrical frequency response of the multimedia head unit output is also measured, which is $X_1 + iY_1$. The filter

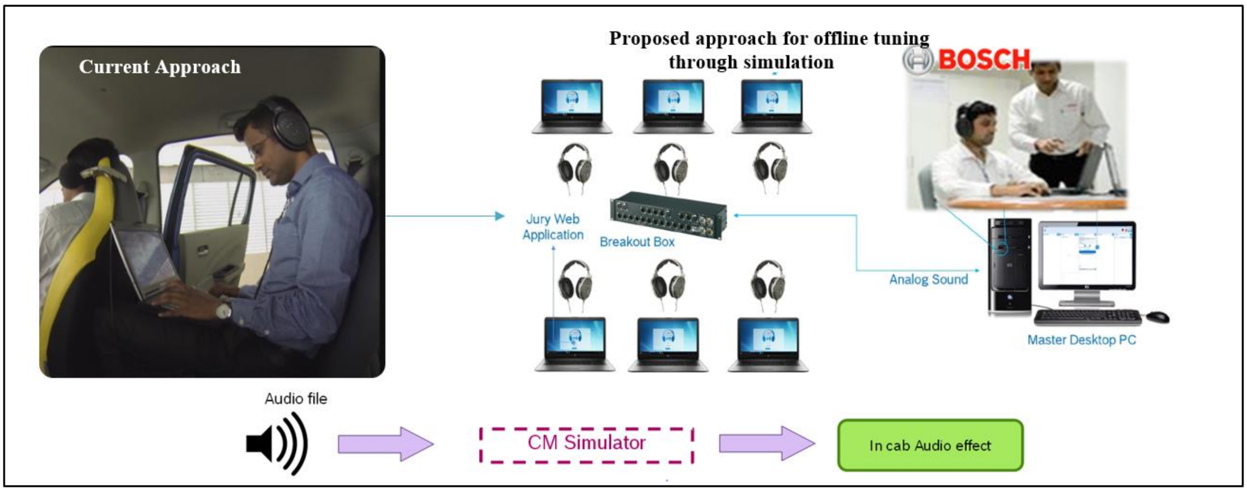

Figure 4. Proposed Tuning Method

function is given by (refer figure 5):

$$\frac{X_2+iY_2}{X_1+iY_1} \quad (1)$$

This filter is specific for that particular location at which the recording was made, i.e., it replicates the audio response at that particular point in the cabin. A recording made at another location in the cabin will have another filter function and this can be easily derived from a recording made at that location. Similarly filter functions are captured at all 4 locations of the cabin (driver ear, rear passenger ear etc.)

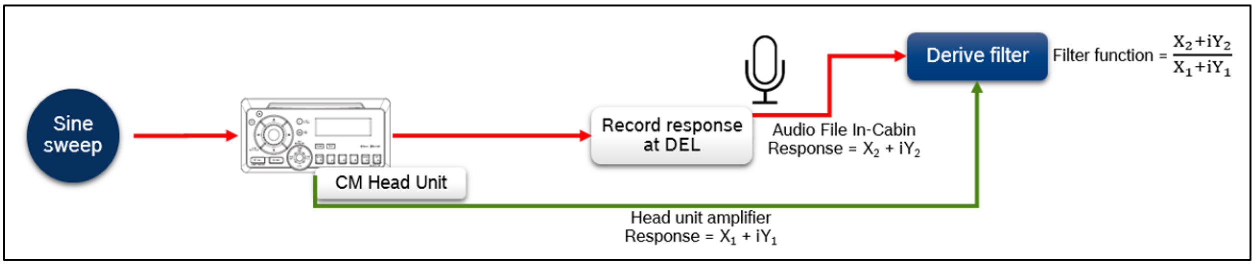

Figure 5. Approach for Filter design

2.3.2. Filter Application

Once the filter for a particular location in the cabin has been derived, it can be applied to any audio/music file to obtain the corresponding frequency response at that point in the cabin. The process involves only the head unit and a signal analysis tool. For every EQ setting (e.g. Flat, rock jazz etc.), the electrical output response of amplifier is measured for any audio file for which jury tests needs to be conducted.

The filter derived in previous method is then applied to the measured electrical response. This produces the new audio frequency response containing the vehicle acoustic characteristics. The sound data is then synthesized back to wav file using iFFT [4]. The design and application of the filter to obtain the audio response at the driver ear level of a particular vehicle cabin is shown in the figure 6 below:

2.4. Validation of FFT-iFFT combination approach

For confirming filters, specific validation tests a passenger car was identified. Test 1 was carried out in the hatchback cabin with binaural head units positioned at the Driver Ear Level, Co passenger Ear Level, Right Rear Passenger Ear Level (Inner), and Left Rear Passenger Ear Level (Inner) as shown in

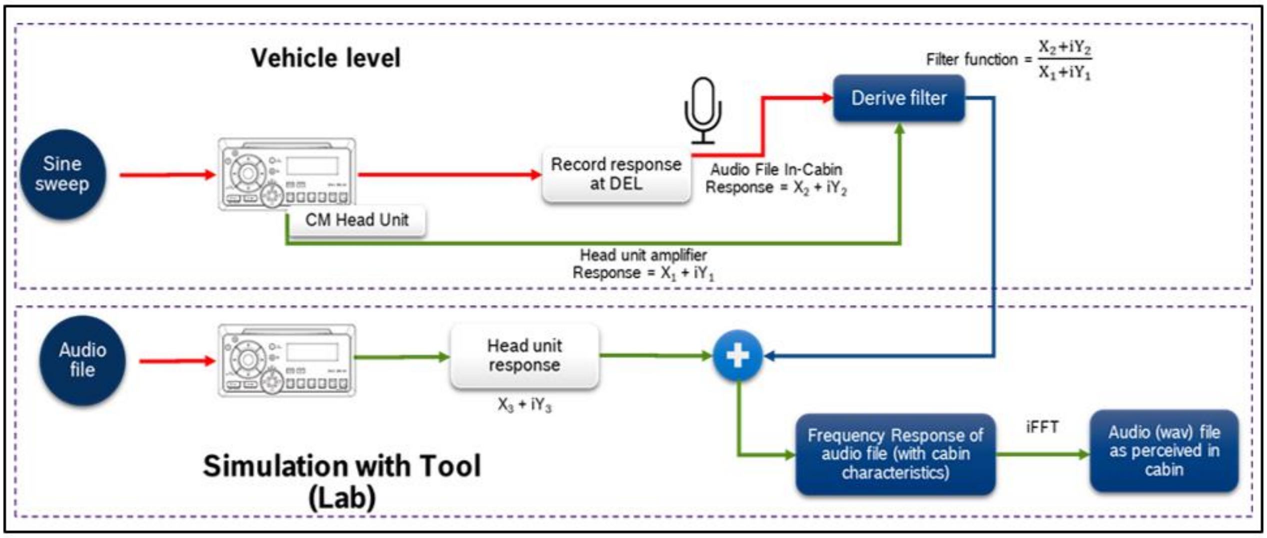

Figure 6. Application of filter to reproduce sound with cabin characteristics

figure 8. The advantage of using a binaural head unit is to ensure that the actual human hearing is replicated as the binaural transfer functions are also captured in the cabin transfer functions [3].

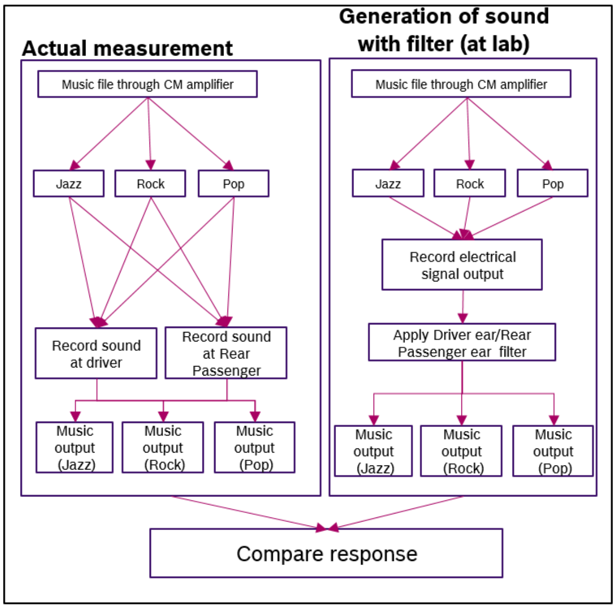

Figure 7. Validation of filter design

The test files were played through the car audio system via bluetooth and recordings were made at the specified seating locations. The digital filter was designed using the sine sweep noise file. The car multimedia system amplifier was set to “flat” equalizer setting. The recordings were made at a fixed volume with the windows closed and the air conditioner turned off. The simulated recordings were then obtained using the captured filter for different equalizer settings in laboratory condition with the FFT-iFFT model.

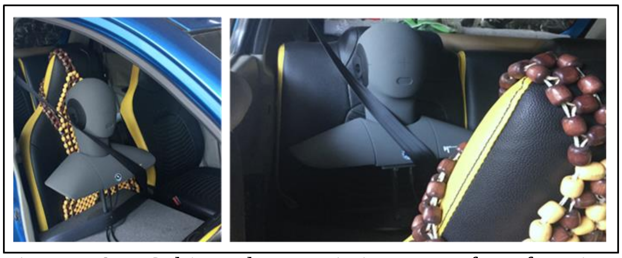

Figure 8. Cabin characteristics transfer function measurements using binaural responses at Driver Ear and Rear Passenger Ear locations

2.4.1. Results

The measured as well as simulated files (with filter), showed no differences in subjective perception. The octave spectrum for two different equalizer settings are indicated in figure 9, 10. Also, the spectral comparison over time shown in figures 11 to 14 indicates minimal difference < 1 dBA across the frequency bands. The filter reproduces a realistic perception of cabin/speaker acoustic properties. Similar validation trials were conducted for multiple equalization settings such as rock, pop, classical etc.

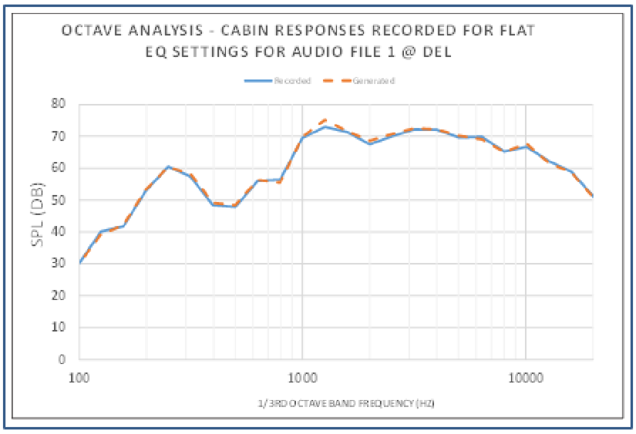

Figure 9. Octave band response comparison for measured and generated music sounds for flat setting

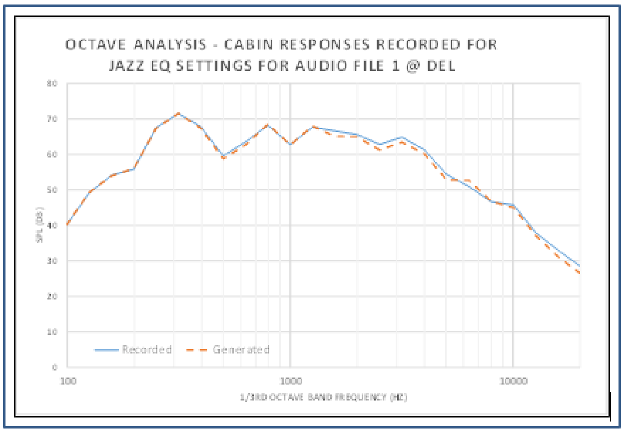

Figure 10. Octave band response comparison for measured and generated music sounds for jazz setting

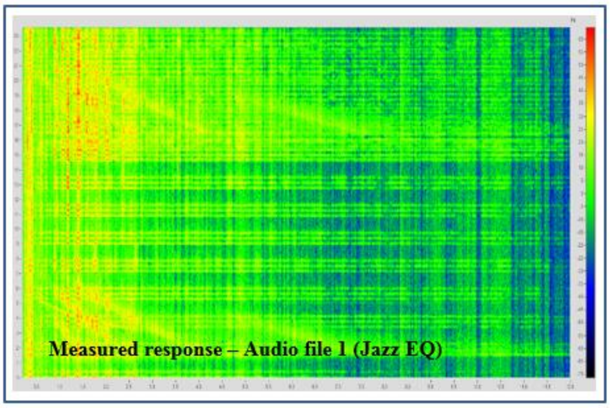

Figure 11. FFT vs time comparison for audio file measured directly in cabin for Jazz EQ settings

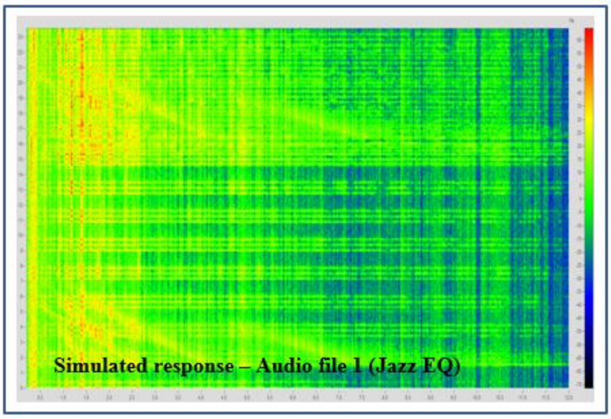

Figure 12. FFT vs time comparison for audio file generated through calculated filter for Jazz EQ settings

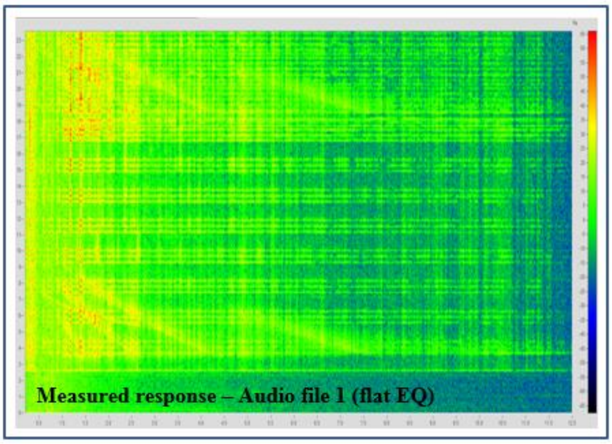

Figure 13. FFT vs time comparison for audio file measured directly in cabin for Flat EQ settings

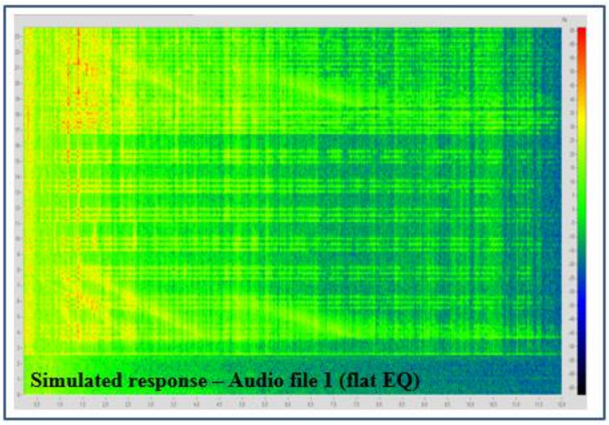

Figure 14. FFT vs time comparison for audio file generated through calculated filter for Flat EQ settings

2.4.2. Jury assessment of audio files

The simulated audio files for 4 equalizer settings were then subjected to juries and the perception ratings was noted through pairwise comparison tests. These ratings were captured for "general pleasantness and sound clarity" as categories for assessment. The tests were repeated for audio files directly recorded in the vehicle level for the same equalizer (EQ) settings.

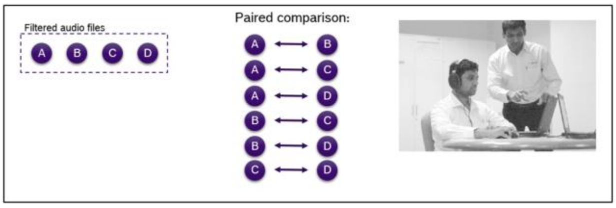

Figure 15. Jury testing using pairwise comparison method for simulated audio files

The subjective results indicate same rating pattern and in both cases, EQ setting "B" was rated as having the most pleasing sound quality. This re-iterates the possibility that this approach can be very well used in the development phase itself in order to front load the equalizer settings design depending on vehicle cabin characteristics.

3. Summary and Conclusion

The new assessment approach for front-loading the equalizer software settings well into the project design phase proves highly effective as the simulated results show minimal or no differences as compared to actual measured responses.

With this approach, sound engineers will be able to tune audio systems in the lab and generate audio files which will include characteristics of vehicle cabin, speaker response and also amplifier characteristics as show in figure 16 below.

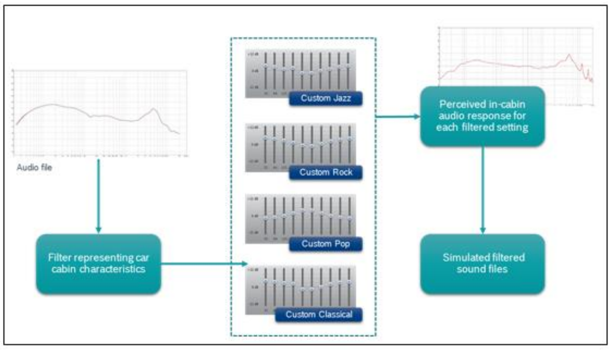

Figure 16. Generation of multiple custom filters through the simulation method to generate audio files.

The generated files can be then subjected to jury tests and best equalization combinations can be obtained for individual hearing locations such as driver ear/co-passenger ear location, rear passenger etc.

The new approach brings significant advantages listed below:

- Assessments take much reduced time (estimated 50-60% reduction in assessment time)
- Minimal dependence of cabin (responses need to be captured only once, for base flat EQ settings).
- Jury evaluations can be conducted rapidly with changes to EQ settings made within minutes.
- Actual cabin perceptions can be perceived well in advance in the design stage itself.

The method can also be explored for other applications, beyond vehicle multimedia systems as well.

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References

1 G. Accardo, M. El-kafafy, B. Peeters, F. Bianciardi, D. Brandolisio, K. Janssens, M. Martarelli, Experimental Acoustic Modal Analysis of an Automotive Cabin, conference proceeding of society of experimental mechanics series available: https://link.springer.com/chapter/10.1007/978-3-319-15236-3_4

2 Jan Fischer, Matthais Behrendt, Dirk Lieske, Albert Albers, IPEK-Institude of Product Engineering, Meausrement and Analysis of the interior noise and transfer path of acoustic phenomena into driver cabin of battery operated electric vehicle.

3 Klaus Genuit, Head Acoustics GmbH, The Sound Quality of vehicle interior noise: a challenge for the NVH-Engineers, Journal of Noise and Vibration, Vol 1, Nos ½, 2004

4 Mathieu Sarrazin, Karl Janssens, Herman Van der Auweraer, Virtual car sound synthesis for brand sound design of hybrid and electric vehicles, SAE Technical paper series 2012-36-0614