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ACOUSTIC DYNAMOMETER MEASUREMENTS AND VIRTUAL PROTOTYPING OF A VEHICLE TO ADDRESS THE LOW FREQUENCY NOISE IN A PASSENGERS CABIN

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ABSTRACT

In the real-world situation, the vibroacoustic behavior of a car at low speeds depends primarily on the engine excitation and road roughness, which will cause the vibration of different elements like doors, roof, windshields, and floor panels. The magnitude of the acoustic response in the passenger's cabin at low frequencies can increase significantly because of noise radiated by those mechanical components. Each of these elements will radiate maximum acoustic power at their natural frequencies excited during the driving process. Different engine frequencies of operation may excite different elements because each element has a different resonance frequency. In this paper, we discuss the innovative approach to understanding these effects where we performed laboratory tests to analyze vibroacoustic effects on a standard car. The car was tested on an acoustic dynamometer installed with rough road shells and equipped with a laser vibrometer to investigate resonances at specific driving speeds. Then there is a possibility of extending the research to FEM vibroacoustic simulation techniques to correlate simulation results with results from the test investigation performed in the unique laboratory.

Keywords: *Dynamometer, vibroacoustic, low-speed operation, resonance frequencies, noise control, 3D-laser vibrometer, FEM simulation, automotive noise reduction.*

1. INTRODUCTION

In today's world, the issue of low-frequency noise and booming effects in passenger cabins are increasingly concerning vehicle manufacturers [1], particularly in electric vehicles. Car wheels hitting an obstacle or driving a rough road cause low-frequency rumble in even the newest hi-class cars. This noise, characterized by its low pitch and often pulsating nature, can lead to discomfort and fatigue among passengers. This creates research opportunities for acoustic experts in the automotive industry. To study this effect-controlled environment replicating real vehicle conditions is required. Controlling the excitation like road surfaces and driving conditions in a stable environment combined with equipment to measure sound and vibrations are factors that make such study possible. Approach that utilizes both vibrational and acoustic responses of a car was extensively studied [2-4].

This paper presents the approach to study mentioned effect by using a unique brand new test stand located in Acoustic Research and Innovation Center (ARIC) by KFB Acoustics in Poland. This test stand is a unique combination of an acoustic dynamometer and a 3D laser Doppler vibrometer operated by a scanning robot (Figure 1). The system is located in the semi-anechoic chamber fully equipped with the sound and vibration acquisition system.

Figure 1: Standard vehicle installed on the dynamometer test stand in D1 acoustic chamber in ARIC.

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This combination gives a range of possibilities for conducting NVH (Noise, Vibration, and Harshness) analysis on vehicles, including:

A. **Low-Frequency Excitation**: Impact bars and road shells simulate road roughness, exciting the vehicle's suspension system and components at low frequencies. This enables studying the vehicle's response and vibration behavior in realistic driving conditions.

B. **Structural Analysis**: The 3D laser vibrometer measures vibrations on vehicle components during dynamometer testing. This data helps analyze structural dynamics, identify resonant frequencies, and detect mode shapes causing unwanted vibrations.

C. **Modal Analysis**: By applying the 3D laser vibrometer to different vehicle components, modal analysis can be performed to determine their natural frequencies, mode shapes, and damping characteristics. This information is crucial for optimizing component design and reducing vibration and noise levels.

D. **Transfer Path Analysis (TPA)**: TPA helps in identifying the paths through which vibrations and noise propagate from the source to the receiver. By combining the measurements from the 3D laser vibrometer with input measurements from the dynamometer, researchers can quantify the contribution of different components and systems to the overall NVH behavior. This analysis enables targeted improvements to be made in the design and isolation of the source and receiver elements.

E. **Acoustic Analysis**: Using a 3D laser vibrometer, vibrations on the vehicle's surfaces are measured and correlated with recorded noise levels in the cabin. This correlation helps identify areas contributing to excessive noise and informs the design of noise control measures, such as insulation and absorptive materials, to improve passenger comfort.

F. **Tire Noise Analysis:** The acoustic dyno also serves as a perfect environment to assess tire-road noise. The crucial point is the ability to assess noise and vibration when the car encounters different kinds of obstacles on a road. In acoustic dyno, those kinds of experiments can be conducted in a very repetitive manner.

Overall, the combination of a Semi-anechoic Dynamometer facility and a 3D laser vibrometer provides researchers with a comprehensive set of tools for NVH analysis. These techniques enable the identification of sources, characterization of structural dynamics, and development of targeted solutions to optimize vehicle comfort and reduce noise and vibrations.

After collecting experimental data, researchers can utilize the recorded noise and vibration measurements to fine-tune the Finite Element Method (FEM) models to study low-frequency phenomena. Signal processing of the measured data involves employing techniques like spectral analysis and other approaches to identify primary frequencies and potential sources. Correlations between low-frequency noise and factors such as vehicle speed, engine RPM, and suspension characteristics can be explored. The FEM study provides insights into car vibroacoustic behavior and aids in optimizing noise and vibration levels. This comprehensive approach enables researchers to uncover the root causes and effects of low-frequency noise in passenger cabins, facilitating the development of effective noise mitigation strategies and enhancing passenger comfort and well-being.

2. METHODOLOGY

In the present study we conducted acoustic measurements on the dynamometer test bench to characterize the low-frequency noise. Then, we measured car body surface vibrations using the 3D-laser vibrometer on the vehicle to assess the impact of low-frequency excitation for selected operating conditions.

2.1 Excitation

The surface of the dynamometer rollers was equipped with a special type of uniquely designed road shells (Stone mixture composition) as shown in Figure 2 to excite the low-frequency broadband excitation. The importance of road roughness to a car vibroacoustic response was extensively studied [5-9].

Figure 2: Road shells installed on the roller test bench for low-frequency excitation.

Installing impact bars on the rollers is also possible (this replicates real-world obstacles, see Figure 3). This configuration causes repeatable events (pulses), which introduce more complexity to the analysis. In this study, only road excitation is used. The car was set on neutral gear with the engine turned off.

Figure 3: Impact bars installed on the roller. A visible smooth surface of the roller in case of road excitation is not needed.

2.2 Measurement Setup in the car

The vehicle was fixed with single point fixation on front towing hook and with the lashing belts on the rear side towing hook of the vehicle. The transducers and sensors were fixed inside and outside of the vehicle. Two sets of artificial headsets were used in the front passenger seat and back passenger seat (Figure 4).

Figure 4: Instrumentation set-up inside the vehicle.

During the initial phase of the experiment, the vehicle started from a standstill and steadily increased its speed up to 50 km/h. This gradual acceleration ensured that any problematic conditions would be more likely to manifest, enabling us to capture valuable data for analysis. By carefully monitoring the vehicle's behavior throughout this process, we aimed to pinpoint any irregularities or abnormal vibrations that might indicate underlying problems.

2.3 3D-Laser Vibrometer Setup

To achieve a comprehensive understanding of the vehicle's dynamics, we used a state-of-the-art 3D-laser vibrometer study (Figure 5). This advanced technology allowed us to precisely measure and analyze the vibrations of various components within the vehicle. Mapping the vibration patterns in a three-dimensional space gave valuable insights into the vehicle's performance under different conditions and speeds.

Figure 5: 3D-Laser vibrometer setup for scanning the surface vibration.

The combination of the gradual acceleration experiment for acoustic study and the 3D-laser vibrometer for vibration study provides a robust foundation for further diagnosis. By comparing the collected data with established benchmarks and conducting detailed analysis, we can effectively identify the root causes of any problematic speeding conditions.

2.4 FEM Simulation

Using FEM simulation, researcher can virtually model critical component and test it under realistic driving conditions, including loads, forces, and vibrations [10]. This provided valuable insights into its structural dynamics and mode shapes, revealing potential weaknesses. Comparing the simulation results with actual test data allowed us to assess the accuracy and predictive capabilities of our model. This validation process bolstered our confidence in the simulation technique's ability to replicate real-world behavior. The findings from the FEM simulation provided valuable information about how the critical component responded to different stress levels and vibrations. This knowledge enabled researchers to make decisions regarding potential design modifications, material enhancements, or structural reinforcements to improve the component's performance and durability.

3. DIAGNOSTIC RESULT

3.1 Vibro-Acoustic Results

Figures 6 to 8 present the acoustic results for 0-50 km/h gradual acceleration of the vehicle.

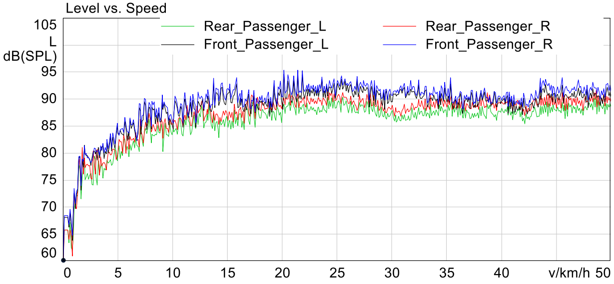

Figure 6: Sound Pressure Level vs 0-50 kmph gradual acceleration plot.

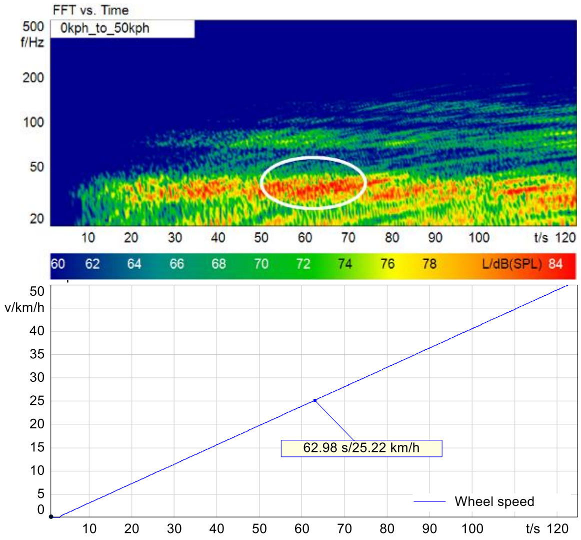

Figure 7: Speed vs Time plot to identify the problematic driving speed.

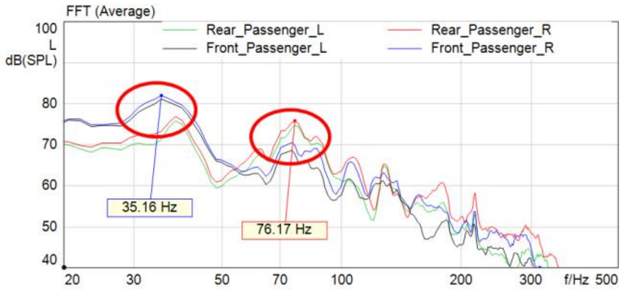

Figure 8: FFT Plot of cabin sound pressure - constant speed 25 km/h.

The acoustic study revealed that dominating frequencies are located around 40 Hz & 80 Hz. Those frequencies were responsible for the significant increase of sound pressure level inside the cabin. 25 km/h was selected as the car speed with the highest amplitude for those frequency bands.

3.2 Individual excitation Study of Acoustic rollers

In the Dynamometer study, distinct components such as front and rear axles can be individually analyzed by applying stimulation to different rollers. Figure 9 illustrates the level comparison under identical operating conditions, focusing on the impact of front and rear roller excitations. The front axle causes higher sound levels in most of the analyzed frequency bands.

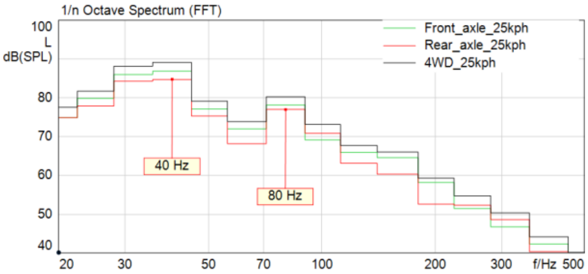

Figure 9: 1/3-octave bands comparison of Front Axle, Rear Axle and 4WD excitation on dynamometer – 25 km/h car speed.

3.3 3D-laser vibrometer results

Vibration scanning was performed at 25 km/h car speed. Main cabin elements related to the car interior were scanned as shown in Figure 10 (roof, side windows, back window, side doors).

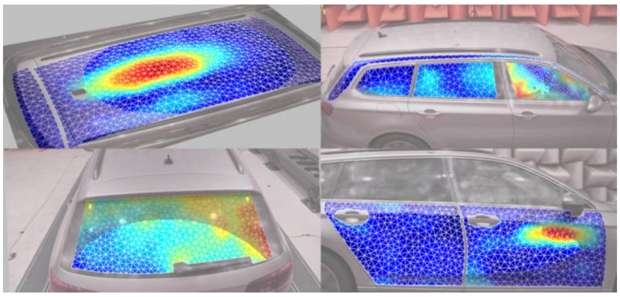

Figure 10: Element for vibration scanning: roof, side windows, back window, side doors.

For considered frequency bands (40 Hz and 80 Hz) frequencies associated with the highest velocity magnitude were selected to present the form of vibrations (Figure 11).

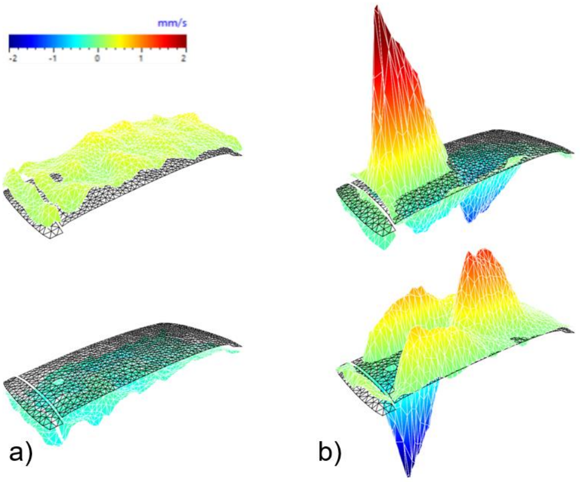

Figure 11: Vibration velocity for the roof of the car cabin:
a) 36 Hz, b) 81 Hz.

Based on the measurements it can be found that at 81 Hz the structural mode of the roof can be easily recognized. But for 36 Hz the whole roof surface vibrates in phase (Figure 11a). For deeper understanding of this phenomena, a whole car cabin behavior at this frequency vibration is presented on the 3D model (Figure 12). It can be seen form figure 12, that each cabin element exhibits the same pumping motion. This vibration pattern can be associated with a global mode of the cabin.

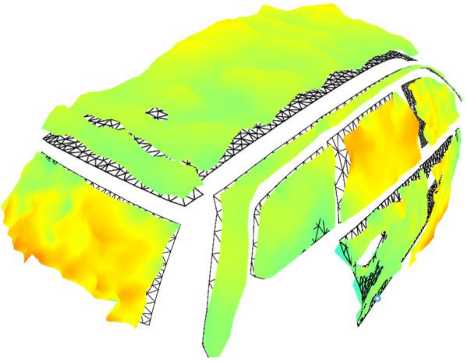

Figure 4 Global mode of the car cabin at 36 Hz.

3.4 Open and Closed window acoustic study

To find out basic nature of the identified global mode at 36 Hz (Figure 12) additional measurements with open window were performed (Figure 13). The goal was to confirm the air cavity role in the mass-spring system with car cabin structure. The role of the acoustic cavity in the vibroacoustic response was also studied by others before [11].

Figure 13: Car with all windows opened.

Measurements show that opening windows causes a significant sound level drop (Figure 14) and vibration magnitude drop (Figure 15) at the 40 Hz frequency band.

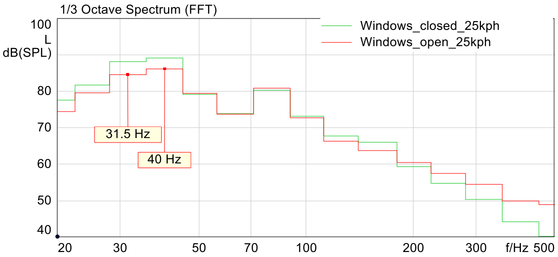

Figure 14: 1/3-octave bands comparison of Open and Closed window.

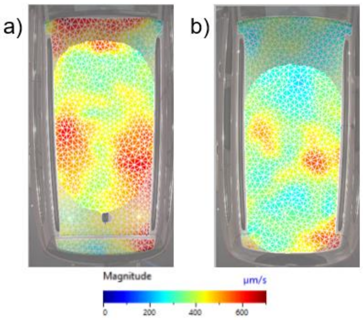

Figure 15: Vibration velocity magnitude of the rooftop at 40 Hz 1/3 octave band: a) all windows closed b) all windows opened.

Figure 16 shows the difference in rooftop vibration velocity average spectrum with all windows closed and open. The biggest difference can be noticed in the mentioned 40 Hz frequency. This suggests that indeed the stiffness of air filling the cabin plays an essential role in forming this global mode.

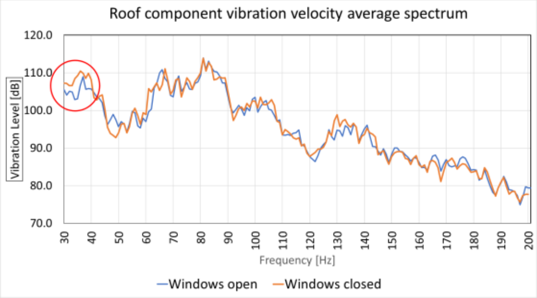

Figure 16: Rooftop vibration velocity average spectrum, window open and window closed.

3.5 FEM simulation

The local and global modes can be treated and dealt with individually by performing various structural modifications and changing the boundary conditions. To make this process cost and time effective, the whole vibro-acoustics optimization procedure can be performed on the calibrated virtual prototypes (e.g., FEM or SEA models). For example, consider an individual element of a car, say a side window. Figure 17 & 18 shows the measured and simulated mode shapes of this part. By introducing changes in the model, it is possible to tune the virtual prototype so that eigenvalues match with those obtained on the real object. In this particular case, we obtained the relative error of the simulation equal to -3% for the 132 Hz mode and -5% for the 186 Hz mode. Obviously, the match of the simulation and experiments depends highly on simulation model details (material, boundary conditions).

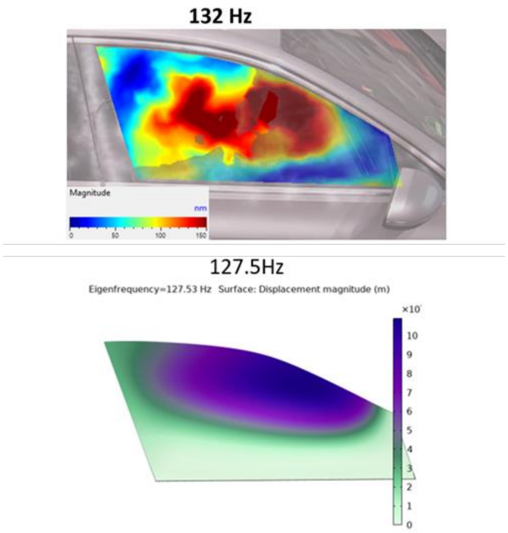

Figure 17: Measured and Simulated modes shapes of side window corresponding to 132Hz

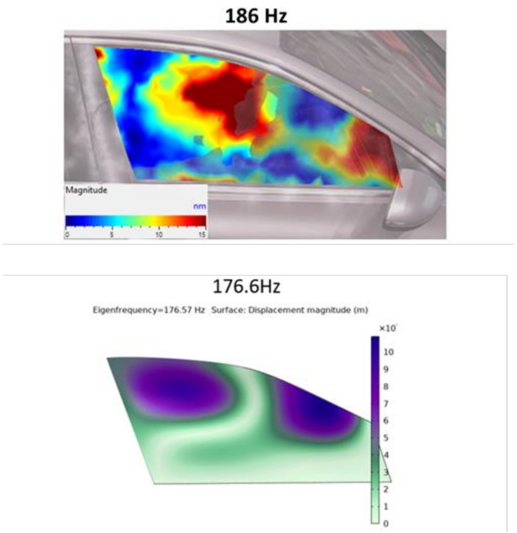

Figure 18: Measured and Simulated modes shapes of side window corresponding to 186Hz

4. CONCLUSIONS

In conclusion, this paper explores the vibroacoustic behaviour of a car in real-world situations, with a focus on low speeds with boom noise heard during driving on a rough road or when the wheels hit an obstacle.

Utilizing an acoustic dyno combined with a 3D laser vibrometer enables us to perform vibration measurements on the whole car body in the same operating conditions. As a result, we identify global modes that can have a significant contribution to the passenger's cabin noise. Global modes occur at lower frequencies and contribute to the booming noise perceived by car passengers. Those modes can be associated either with total car structural assembly or structural assembly coupled with an acoustic system (air inside the passenger's cabin). In the latter case, the car can undergo the well-known mass-spring resonance, where the air inside the cabin introduces stiffness and plays the role of a spring. The mentioned effect couldn't be identified by measuring individual parts of the car separately. This clearly shows the advantage of utilizing the 3D laser vibrometer and the acoustic dyno together, where the whole car vibrations can be scanned without partitioning the car structure during simulated driving conditions. Conversely, when a problem occurs at higher frequencies, one can identify the local modes of individual parts with ease by analyzing the measured mode shapes.

The insights derived from the advanced dynamometer test facility have expanded the understanding of the vibroacoustic effects on the car. Vehicle manufacturers can identify potential areas for improvement in the vehicle's design and performance, paving the way for enhanced noise reduction strategies and overall vehicle refinement.

Current achievements of the automotive industry regarding lighter car body parts with optimized structures to avoid important local modes, eliminated engine noise and quieter components are significant but the low-frequency behavior of a car cabin is still a challenge for researchers and engineers.

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