Department of Mechanical and Aerospace Engineering

Master's Thesis in Automotive Engineering

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Analysis and Optimization of the Vibrational Response of an Automotive Seat

Design Solutions for Improving Comfort and Performance
in collaboration with Sabelt S.P.A.

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Abstract

The present thesis project, conducted entirely at Sabelt S.P.A., aims to analyze and improve the vibrational response of an automotive seat, highlighting the parameters that affect its performance in simulated test environments. Sabelt S.P.A., a leader in high-performance seating solutions for the automotive industry, provided technical expertise and laboratory resources, supporting experimental research aimed at enhancing the performance, durability, and comfort of the analyzed seat. The primary objective is to understand the dynamic behavior of the seat subjected to various excitation conditions, with stresses applied by shakers available in the Sabelt laboratory. The research not only involves a simple evaluation of the vibrational response, but also aims to identify and propose design or material improvements to reduce the negative effects of vibrations on the structure and enhance occupant comfort. To obtain an accurate assessment of the seat's dynamic response, excitation signals are applied using a mono-axial shaker, simulating real-use conditions in the anechoic chamber in the Sabelt's laboratory by controlling the intensity of the excitation. The experimental analysis is enriched by data processing and frequency analysis tools, which allow the detection of any resonances or critical points where the seat structure shows increased vulnerability. This analysis is essential to identify structural characteristics that may require optimization. This thesis represents a contribution to the development of an effective response to external stresses in a seat. The work demonstrates the importance of ensuring that automotive seats maintain a high-quality standard and meet consumer demands for comfort while ensuring safety.

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Chapter 1

Introduction

In the modern context of the automotive industry, the seat is one of the most important components of a vehicle, as it directly affects the safety and comfort of the occupant. Today, the expectations of an automotive seat go beyond safety to comfort and aesthetic quality. In a market where consumers are increasingly asking for vehicles that can provide them an enjoyable driving experience, the need to design seats that would protect the occupants as well as keep them comfortable during the journey is increasingly a lot. Comfort in a car seat would depend on the seat's ability to damp unwanted vibrations coming from asphalt and external excitations, traveling through wheels and chassis to the seat, and manifesting as noise that is transmitted to the occupant. A well designed seat would be able to damp these types of vibrations in order to reduce any possible discomfort that might arise with long travels or proronged periods of time. It is a fact that constant vibrations and noise create physical and mental stress, leading to fatigue and discomfort, considerably reducing perceived comfort. The present thesis focuses on the analysis and optimization of the response of a car seat excited by a mono-axial shaker in a semi-anechoic chamber. The model under study is the seat of the Abarth 595 vehicle model produced up to summer 2024, a structure with the right trade-off between strength and lightness but showing noise and vibration levels within the cabin that are higher than the threshold desired in laboratory conditions at the stage of the preliminary tests. The semi-anechoic chamber was chosen in order not to interfere with the outside environment in acoustics and vibration, ensuring that the data collected accurately reflect the seat's dynamic behavior when operating in isolated conditions. In order to make this project as close to the reality as possible, the created paths simulate real movements of vehicles on real tracks while producing different noise levels to which occupants would be exposed. The vibrational response in the seat is analyzed by making use of frequency analysis tools; allowing the identification of resonances and those critical frequencies that could negatively affect comfort. Nevertheless, it is important to underline that some information, images and test results cannot be shown in the present thesis for corporate reasons of privacy and in accordance with confidentiality constraints imposed by Sabelt. Moreover, the final design obtained does not represent the seat that is used in real production. Even if this does not allow a complete sharing of some technical data, this does not affect the goal of providing a rigorous and detailed presentation of the methodology adopted and the main results concerning the vibrational response of the seat. A complete report of the procedures and general observations will be provided, respecting the corporate requirements of confidentiality.

1.1 Sabelt: A Legacy of Innovation in Automotive Safety and Engineering

Figure 1.1: Sabelt Plant

With headquarters in Moncalieri near Turin, Italy, Sabelt S.p.A. is a leading company in the automotive and motorsport business sectors, thanks to its innovative products in the field of safety and restraint systems. The company was founded in 1972 by Piero and Giorgio Marsiaj, and its name, formed from "Safety Belt," describes the original product for which the company was initially known: high-performance safety belts. The same Sabelt that, in the following years, heavily enlarged its range, supplying OEMs with specific sitting solutions, or even entering the aerospace sector, providing sophisticated retention systems also used during space missions. Sabelt today holds a prestigious reputation at an international level, with the most rigid standard for safety, quality, and durability, supplying seats and belts to top automotive brands like Ferrari, McLaren, Bugatti, Aston Martin, as well as numerous Formula 1 teams.

1.1.1 History and growth

In the company early years, innovation came fast with the production of its first racing seatbelt in 1976. Its incorporation with TRW in 1985 allowed Sabelt to expand its capabilities to airbag integration and restraint systems. Reacquired by the Marsiaj family in 2000, Sabelt soon diversified into seats, motorsport clothing, and accessories.

Figure 1.2: Ferrari F430 Sabelt Seat

The big deal was with Ferrari in 2006 for a special seat on the Ferrari F430 Scuderia. This deal also made Sabelt take part in the high-performance OEM market. Not only does Sabelt work for the automobile industry, but it also manufactures aerospace retaining systems that are fitted onto the Cygnus spacecraft, which supplies the International Space Station. This will involve Sabelt's commitment to the UN's 2030 Sustainable Development Goals; it has therefore committed to sustainable practices across its value chain, putting up a framework toward long-term ESG milestones. The company received a Silver Badge in EcoVadis' rating platform, a provider of ratings for businesses relative to sustainability performance. Further, Sabelt actually follows supply chain sustainability concerning human rights evaluation of its suppliers, environmental standards, and ethical business behavior. Once again, this commitment affirms industry leadership for Sabelt, focused on innovative design as well as responsible manufacturing to meet the demands of modern automotive and aerospace applications. In the last few years, the growth of Sabelt has continued: in five years it hired more than 200 employees and is willing to hire another 150 professionals. This development, in difficult conditions of the global market, testifies to Sabelt's commitment to a long-term relationship with business partners, product quality, and customer service. Among others, the wide use of lightweight materials like but not limited to titanium and carbon composites that reduce the mass without compromising safety underlines the ability of the company to merge technical excellence with aesthetical appeal. Thus, Sabelt high-quality products meet serious requirements of performance and luxury markets where the main criteria are safety, style, and functionality.

1.2 Sabelt's Laboratory

Sabelt's testing laboratories are an essential part of the company's commitment to producing high-performance, safe, and durable products for the automotive and motorsport industries. These labs play a critical role in ensuring that Sabelt's products, such as racing seats, seatbelts, and other automotive safety systems, meet or exceed stringent industry standards. In this section, the most important tests are shown and explained.

1.2.1 Dynamic Testing and Crash Simulation

Figure 1.3: Dynamic Testing System

Sabelt was among the first companies in the sector to equip its laboratories with advanced dynamic testing systems able to simulate crash scenarios. This enables them to conduct thorough safety tests for products in line with ECE (Economic Commission for Europe) regulations and FIA (Fédération Internationale de l'Automobile) standards, which are required for motorsport applications. These dynamic crash tests simulate real-life impacts that seatbelt systems and seats should withstand without compromising safety. The tests also cover the durability of the products under repetitive use, ensuring that they are safe over time and through various conditions of stress.

1.2.2 Fatigue Test Bench for Electric Motors

Figure 1.4: Electric Motor Test Bench

This test simulates the long working cycles of the motor in conditions that mimic real use, such as its resistance, reliability, and durability, with the intention of maintaining performance constant over time. The test bench will be designed for repetitive operational cycles with the motors that simulate seat tilting and translational movements, repeated. A weight simulates the human presence, usually with a value considered for such tests at 75 Kg to better simulate real-life. In these tests, torque, energy consumption, and failure events are observed. These results are useful in identifying areas of improvement, optimizing the product design, and guaranteeing the quality standards of vehicle manufacturers.

1.2.3 Seatbelt buckle testing

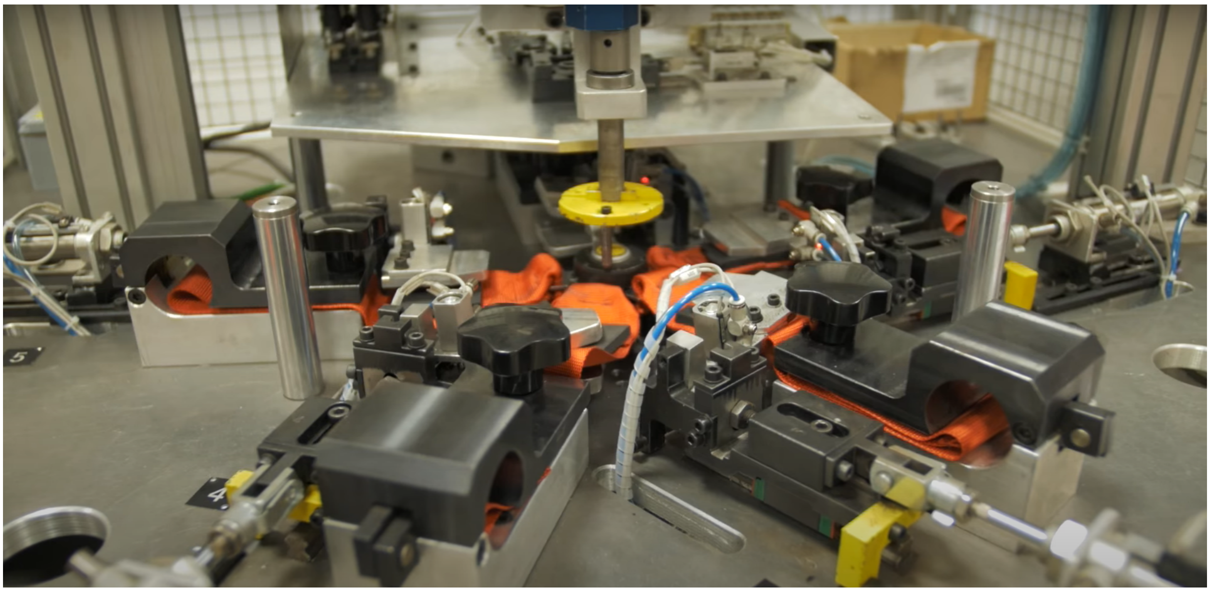

Figure 1.5: Sabelt Racing Seatbelt Buckle Testing

Sabelt rigorously tests all of its competition seatbelt buckles for the highly demanding levels of safety and reliability required in motorsport. These tests take real-world stresses and verify that the performance under extreme conditions is, at least, sufficient. One such test on this buckle can be seen in Figure 1.5, where the seatbelt buckle has undergone 5,000 opening and closing cycles. This process verifies not only the mechanical strength of the buckle but also its ability to maintain safety standards through repeated use. The testing also ensures that the buckle can operate efficiently and reliably at the crucial moments of the race, such as changing the driver. This is because each fraction of a second lost may mean several seconds, which are significant in races and may impact the outcome of the competition.

1.2.4 Micro-slip tests

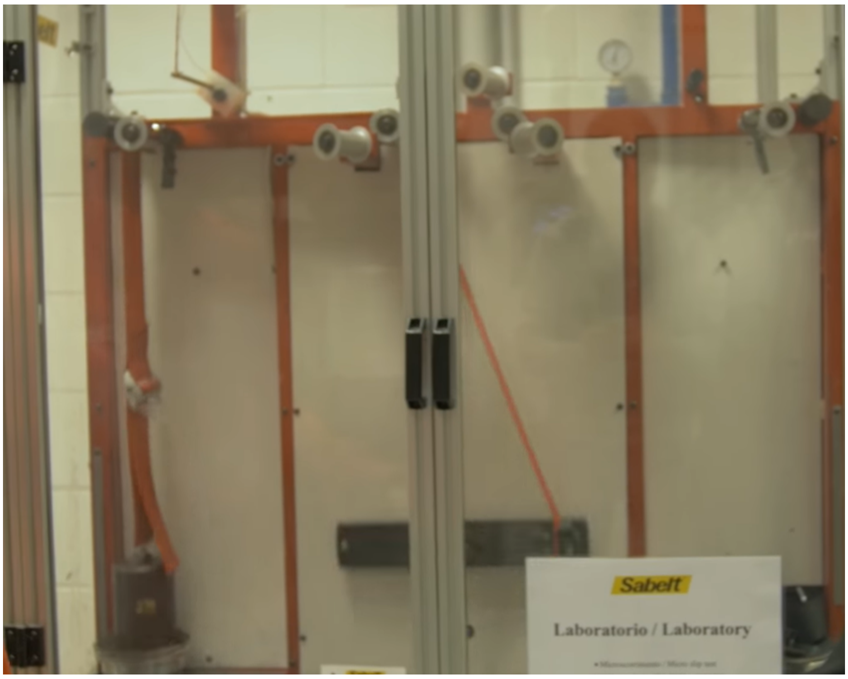

Figure 1.6: Test System

Sabelt performs micro-slip tests on its seatbelt systems with the rigor necessitated by high-demand motorsport applications. These tests verify that the regulator can maintain consistent tension on the webbing, so it does not slack in use, a prerequisite for both safety and driver performance. A seatbelt regulator undergoes 1,000 consecutive tension-release cycles during a micro-slip test. These cycles simulate forces that can be considered 'real world' condition, that is experienced in both driver movements and crash scenarios. In the course of this test, a system's capability to firmly grip the belt without any slippage is assessed. Mainly, this test aims at keeping the belt taut to avoid some looseness that could create unsafe or uncomfortable conditions. A good regulator will keep the belt tightly fastened to always provide the same tension over its lifetime. For a motorist engaged in motorsports, this is very critical; any loose belt might cause more than a safety hazard and could interfere with the driver concentration during a race.

1.2.5 Seatbelt tensile test

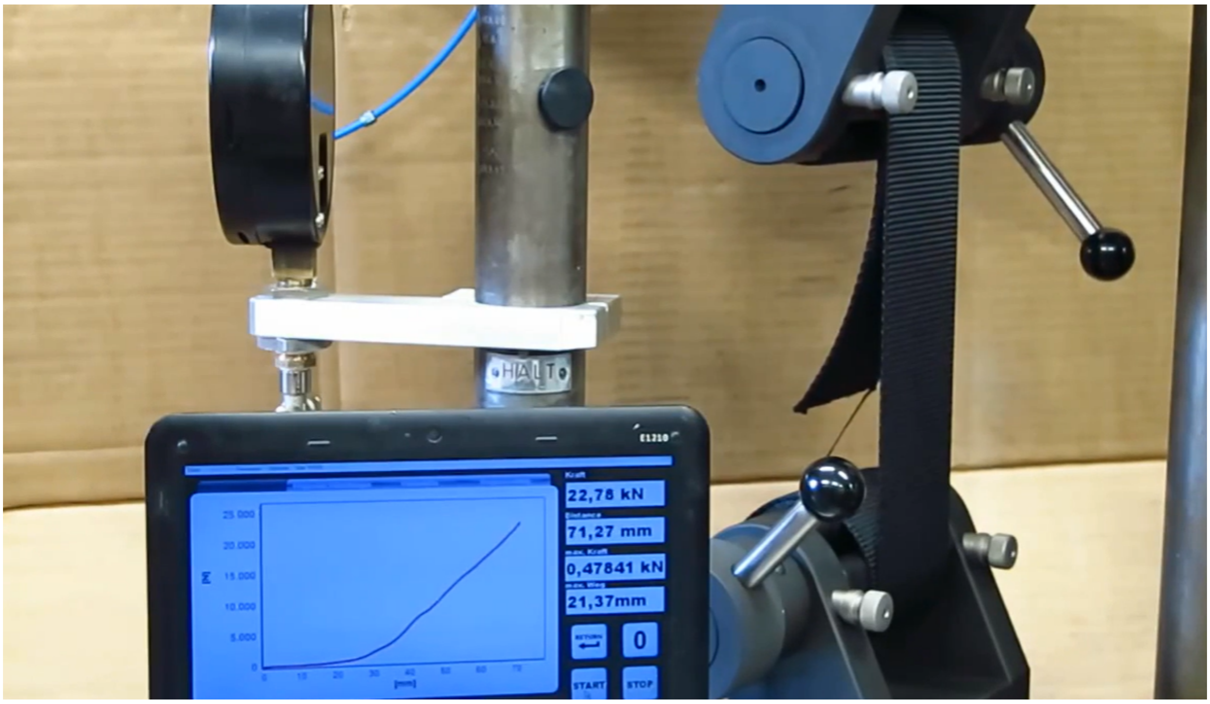

Figure 1.7: Seatbelt Tensile Test

The tensile test of the seatbelt is one of the most important test procedures that check the capability of a seatbelt to resist most of the intense forces transmitted during high-stress states, such as in conditions of a crash. This includes steadily increasing the force on the seatbelt until it actually breaks and determining the maximum amount of load the webbing can handle before failure. The applied force will be measured by means of load cells during the test and, from these, the seatbelt tensile strength can be calculated. Sabelt aims to exceed the minimum of safety requirements provided by the FIA and ECE regulations so its seatbelts can undergo even more extreme conditions.

1.2.6 Vibrational Noise Test

Figure 1.8: Mono-axial Shaker

The test for vibrational noise using a mono-axial shaker at Sabelt is one of the key tests for simulating those vibrations that any car seat would experience through on the road. It is now desirable to study the reaction of main components of the seat, be it the seat structure itself or the fastening mechanism, in conditions of vibration at frequency levels associated with vehicle movement. The test aims at measuring the noise resulting from seat vibration in order to identify the resonance or unwanted acoustic occurrence of the seat. These could be of various frequencies and amplitudes, each specifically designed to simulate how a drive on smooth highways or even on rough and uneven roads would feel. This laboratory test will be discussed in detail in the following chapters, since this is what the case study of the thesis pertains to.

1.3 Case Study

This sub-chapter provides a general overview of the case study discussed in this thesis, detailing the methodology and approach followed throughout the analysis. It explains the specific steps undertaken by the laboratory team to perform vibration and noise testing on the seat, illustrating the procedures used to replicate real-world conditions.This section ensures a clear understanding of the progression and execution of the case study, by walking the reader through the test setup, data collection and results interpretation.

1.3.1 Generating the Signal

The process begins with the selection of the Power Spectral Density (PSD) function, a mathematical tool that characterizes the acceleration of the vibrations in the frequency domain. The PSD represents the input excitation applied to the seat, and the same signal is repeated in a loop for a predetermined duration. This PSD is typically derived from real driving conditions, measured using accelerometers placed in various parts of a vehicle. Once calculated, the PSD data is transmitted to the Power Amplifier via the EDM software, in form of time-domain acceleration signal. At the end of this stage, the dynamic forces (accelerations) acting on the seat are fully generated.

1.3.2 Shaker Test Setup

The acceleration data is given as input into the shaker system, a machine specifically designed to replicate the vibrational forces that a seat undergoes during typical vehicle operation. The shaker applies these accelerations to the seat in a controlled manner, causing it to vibrate. As the seat vibrates, forces are transmitted through its structure, leading to the movement of molecules within the seat and its surrounding components. This molecular movement generates noise, which is then captured and recorded. The acoustic data obtained during the test is used to create a noise curve, representing the intensity of sound produced by the seat across various frequencies. This curve is essential for analyzing how the seat's structure affects its acoustic and vibrational behavior under such conditions.

1.3.3 Noise Regulation and Standards

To ensure compliance with industry standards, several regulatory frameworks govern the acceptable noise levels for vehicle components. Among the most commonly referenced are the SAE (Society of Automotive Engineers) noise specifications and customer-specific requirements. These standards set permissible limits for noise emissions, ensuring that seat vibrations do not cause excessive discomfort to drivers and passengers. They also outline specific testing procedures, such as the placement of the microphone to capture noise and the positioning of the seat on the shaker. The regulations typically establish maximum allowable noise levels across different frequencies, against which the noise curve from the test is compared to verify compliance.

1.3.4 Analyzing the Results

Once the shaker test is completed, the results are evaluated and categorized as either OK (acceptable) or NOK (not acceptable). An OK result means that the seat complies with the required standards for noise and vibration performance. Conversely, a NOK result indicates that the seat design must be adjusted to reduce noise and enhance performance. To address a OK outcome, several modifications can be implemented, including:

- Application of felt tape or lubricants (such as grease) at critical points where friction or resonance might be causing excessive noise.
- Structural modifications such as adding, removing, or changing the size of tubes or reinforcements to reduce unwanted vibrations.
- A combination of modifications, where multiple changes are implemented simultaneously to achieve the desired noise and vibration performance.

Each modification, or set of changes, generates a new noise curve, which is then compared to the original. This process is repeated until the desired level of noise reduction and vibration attenuation is achieved.

1.3.5 Optimization of the Final Design

Through a series of iterative tests and modifications, the most effective set of improvements is identified. The chosen solution aims to deliver optimal noise reduction while balancing cost and manufacturability. The final configuration ensures the seat adheres to regulatory noise limits without introducing unnecessary complexity or cost. After selecting the optimal modifications, additional analysis is conducted to determine how individual seat components contribute to overall noise at various frequencies. This step identifies specific components responsible for higher noise levels, allowing targeted design refinements. During this phase, hands-on interaction with each part of the seat is crucial. Physically feeling the vibrations provides a deeper understanding and a more accurate assessment of the seat's performance, facilitating precise adjustments to meet performance goals.

Chapter 2

Hints of Theory

2.1 Sound and Noise

Figure 2.1: Sound vs. Noise

Sound and noise are physical events of the same nature but differ significantly in the way they are perceived and used. Sound is a mechanical wave propagating through an elastic medium such as air, liquids, or solids, basically characterized by frequency, intensity, and duration. When sound is perceived as pleasant or useful, such as music or speech, it is typically referred to as "sound." On the other hand, noise is an unwanted or unpleasant sound that may interfere with comfort, communication, or the quality of life. The same physical phenomenon triggers different sensations depending on the psycho-physical-emotional state of the receiver. Noise in automotive can be originated from various internal sources, such as engines, fans, and HVAC systems, or it may come from external sources, such as wind, road surface, or tire interaction. Control and reduction of noise are among the most challenging tasks in the NVH refinement process of a vehicle, since noise directly relates to the comfort of occupants and overall vehicle quality.

2.2 Sound Pressure and Power

Sound is a mechanical wave that propagates through a medium, typically air, in the form of pressure variations. These variations, known as sound pressure, are the fluctuations above and below the ambient atmospheric pressure caused by a vibrating source. Sound pressure and sound power are fundamental concepts in acoustics, each playing a distinct role in understanding and measuring sound. **Sound pressure** refers to the local variations in air pressure caused by sound waves as they propagate through a medium. It is a point-specific measurement that describes the intensity of sound at a given location, expressed in pascals (Pa). For example, sound pressure is what a microphone detects when recording audio or what the human ear perceives as loudness. In contrast, **sound power** is the total acoustic energy emitted by a source per unit of time, measured in watts (W). Unlike sound pressure, sound power is an intrinsic property of the sound source itself and remains constant regardless of the surrounding environment. This distinction makes sound power a valuable metric for comparing the noise output of different sources, such as machinery or loudspeakers, under standardized conditions.

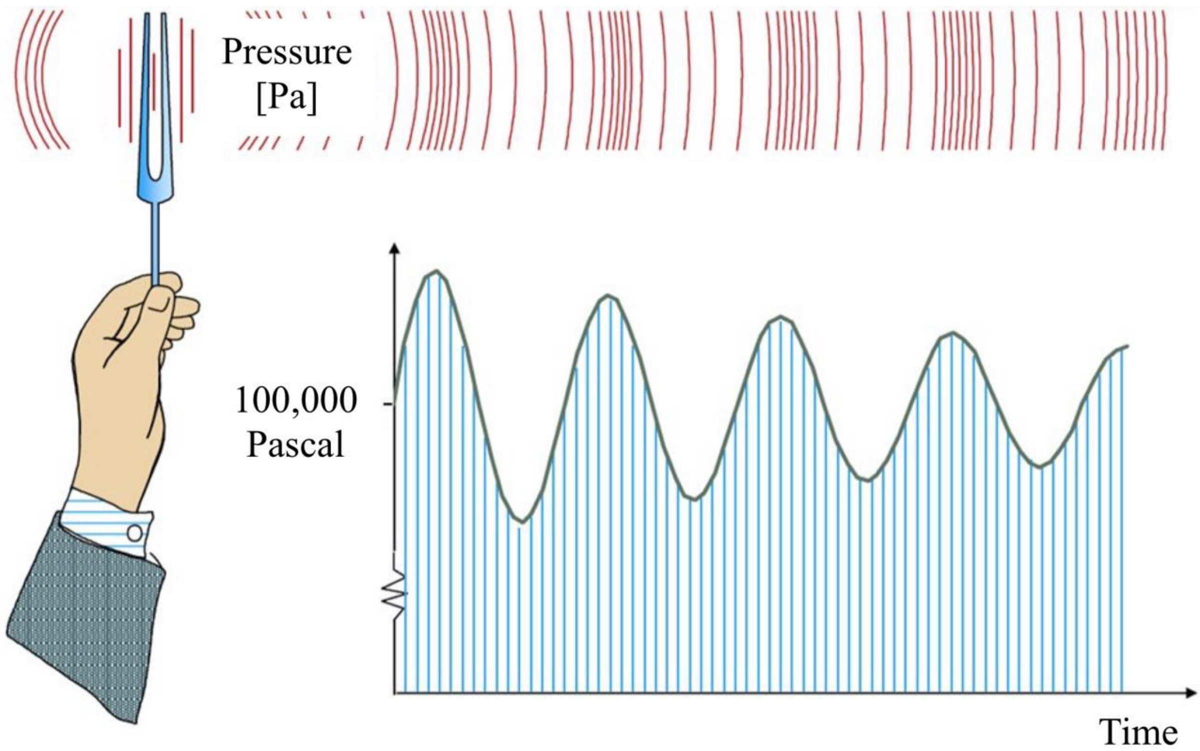

Figure 2.2: Sound Pressure

The sound pressure experienced at a particular location depends on the distance from the sound source and the directionality of the sound waves. Generally, sound pressure is higher closer to the source and decreases with increasing distance. Additionally, the acoustic properties of the space, such as reflections, absorption, and diffusion, affect the measured pressure levels. For instance, reflective surfaces or corners may amplify sound pressure, whereas open spaces or absorptive materials may diminish it. The environment where sound is emitted is crucial in determining how sound pressure is experienced. Factors like air temperature, humidity, and atmospheric pressure can influence sound wave propagation, altering intensity and perceived pressure. Furthermore, the space's acoustics, whether open or enclosed, and the materials within (e.g., walls, furniture, or absorptive materials) significantly impact sound pressure levels. For example, reflective and enclosed environments can enhance reverberation and perceived pressure, whereas open areas or anechoic chambers may reduce it due to minimal reflection and absorption. For example, sound waves in a reflective, enclosed space will tend to reverberate, increasing the perceived pressure, while in an open area or an anechoic chamber, the sound pressure might be lower due to minimal reflection and absorption.

2.3 Sound Intensity Vector

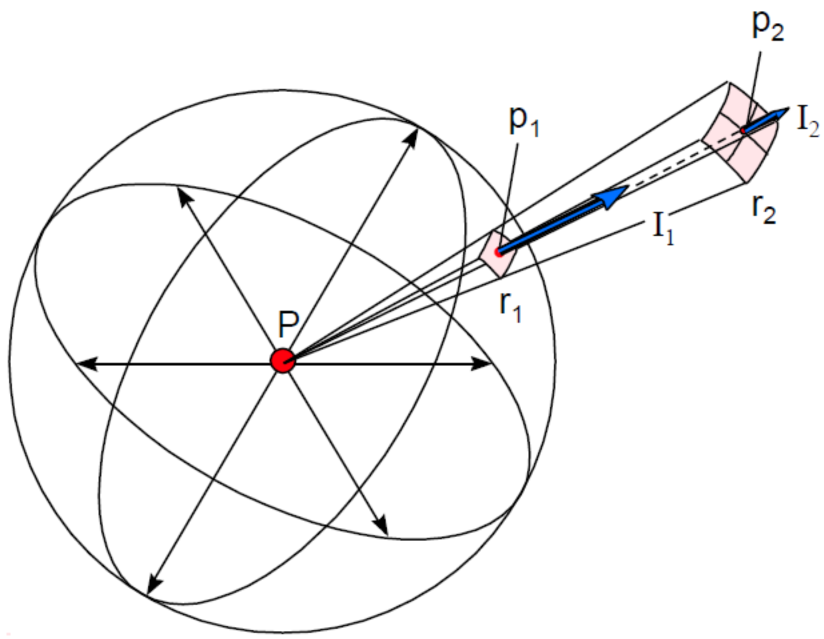

Figure 2.3: Sound Intensity Vector

The **sound intensity vector** is a fundamental concept in acoustics that describes the flow of sound energy through a medium in a specific direction. Unlike sound pressure, which is scalar and provides information about the magnitude of pressure fluctuations, the sound intensity vector is directional and quantifies the power per unit area carried by sound waves.
The sound intensity vector is defined as:

$$I = \frac{W}{4\pi r^2} = \frac{p^2}{\rho c}, \tag{2.1}$$

where:

- W: Sound Power of the source (W);
- r: Distance from the source (m);
- p: RMS sound pressure (Pa);
- ρ: Density of the medium (kg/m^3);
- c: Speed of sound in the medium (m/s).

The direction of the sound intensity vector indicates the direction of energy propagation, while its magnitude corresponds to the rate of energy flow through a given area. For example:

- A high-intensity vector represents strong energy flow, such as near a loudspeaker.
- In regions of reflected sound, the intensity vector may point away from the reflective surface, indicating energy redirection.

In essence, the sound intensity vector represents the average energy flow through a unit area normal to the direction of propagation.

2.4 Sound Pressure Level (SPL)

Sound Pressure Level (SPL) is a widely used parameter in acoustics, providing a quantitative measure of the pressure fluctuations caused by a sound wave relative to a reference pressure. It is expressed in decibels (dB), a logarithmic scale that simplifies the representation of the vast range of sound pressures detectable by the human ear. The formula for calculating SPL is:

$$SPL = 20\log_{10}\left(\frac{p}{p_{ref}}\right), \tag{2.2}$$

where:

- p: The effective sound pressure measured in Pascals (Pa);
- $p_{ref} = 20\,\mu$Pa: The reference pressure, corresponding to the threshold of human hearing in air.

The logarithmic nature of this formula compresses the immense range of sound pressures into a manageable scale. For example, an increase of 6dB corresponds to a doubling of sound pressure amplitude. The range of sound pressure levels (SPL) encountered in everyday life spans several orders of magnitude, as shown in the Figure 2.4 below.

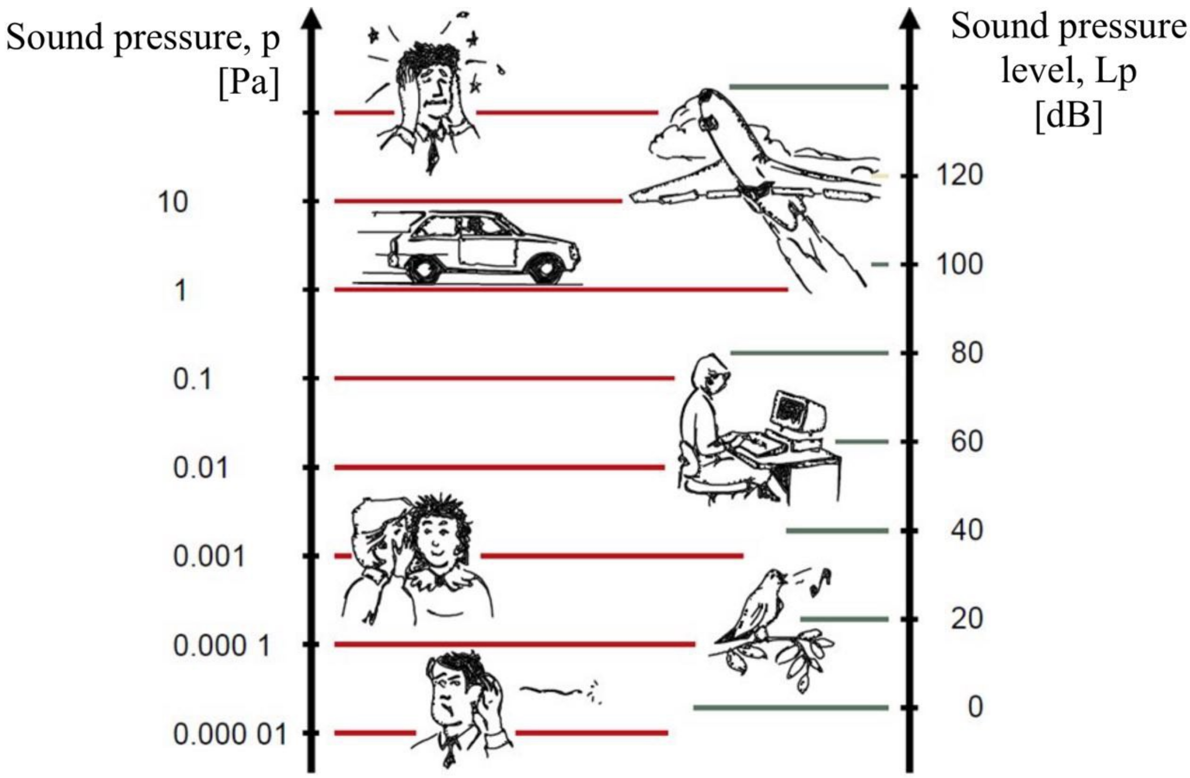

Figure 2.4: Sound Pressure Level

At the lower end of the scale, a quiet environment such as a soundproof room or rustling leaves typically registers at around 20-30 dB, which is near the threshold of human hearing. Normal conversation occurs at approximately 60-70 dB, while sounds such as heavy traffic or a noisy restaurant range between 80-90 dB. At the upper extreme, sounds exceeding 120 dB, such as a rock concert or a jet engine at close range, approach the threshold of pain, where prolonged exposure can cause hearing damage. Loudness is the subjective perception of the intensity of a sound as experienced by the human ear and brain. While it is closely related to sound pressure level (SPL), loudness is not directly proportional to SPL because the human auditory system perceives different frequencies with varying sensitivity. For instance, the ear is more sensitive to mid-range frequencies (around 2,000–5,000 Hz) compared to very low or high frequencies. This sensitivity is accounted for using frequency-weighting filters, such as the A-weighting, which adjusts sound measurements to better reflect human perception. The relationship between sound pressure and perceived loudness is logarithmic, meaning that doubling the sound pressure does not double the perceived loudness. Instead, loudness typically doubles with an increase of about 10 dB in sound pressure level. This is described by the Stevens' power law[1], which links physical sound intensity to perceived loudness.

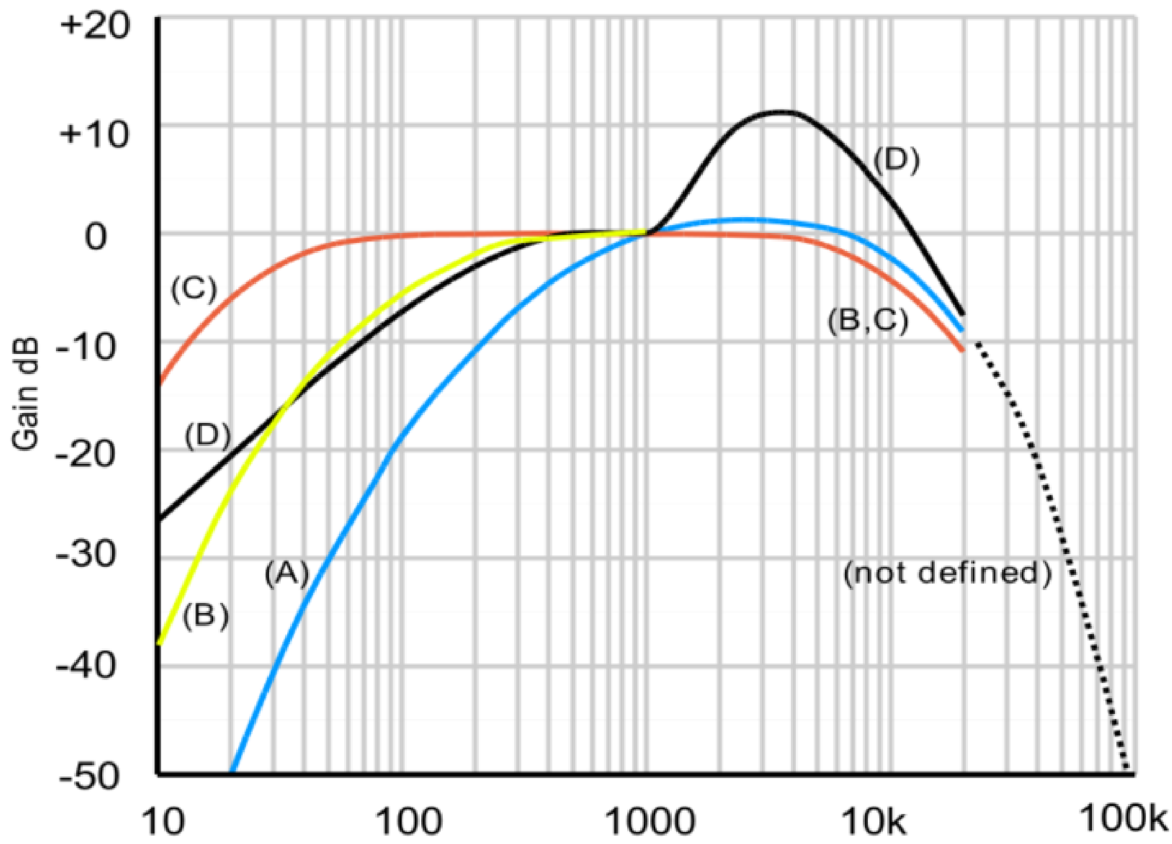

Figure 2.5: Frequency Weighting Curves

The Figure 2.5: Frequency Weighting Curves illustrates the different frequency weighting curves (A, B, C, and D) used to model human perception of sound across varying frequencies. These curves account for the varying sensitivity of the human ear, particularly at low and high frequencies, by applying different levels of attenuation or amplification depending on the frequency. A precise description is shown below:

- A-weighting (blue curve): This curve closely mimics the ear's sensitivity at low sound levels and is widely used for general noise measurements. It attenuates low and high frequencies significantly, focusing on mid-range frequencies (1,000–5,000 Hz), where human sensitivity is highest.
- B-weighting (yellow curve): Less commonly used, it represents the ear's sensitivity at moderate sound levels. It applies less attenuation to low frequencies compared to A-weighting.
- C-weighting (red curve): This curve provides nearly flat attenuation, suitable for measuring high sound levels where the ear is more uniformly sensitive across frequencies.
- D-weighting (black curve): Designed specifically for measuring aircraft noise, this weighting emphasizes the 2,000–10,000 Hz range, where the ear is especially sensitive to these specific sounds.

The graph also highlights the gain levels in decibels (dB) for each weighting, plotted across a logarithmic frequency scale. It demonstrates how these weightings adjust sound measurements to reflect perceived loudness more accurately. In this case study, Sabelt laboratory in concordance with the end customer, are evaluating and mitigating noise coming from the seat to enhance occupant comfort, while ensuring that sound levels remain within acceptable limits for hearing health and regulatory compliance. As it will be shown later, there will be different norms that regulate the SPL at each frequency.

2.5 Frequency Analysis of Sound

Frequency analysis decomposes a sound signal into its constituent frequencies, allowing to go into deeper into its harmonic components and overall spectral content. This analysis is made to understand the behavior of sound waves in different environments, focusing in automotive acoustics.

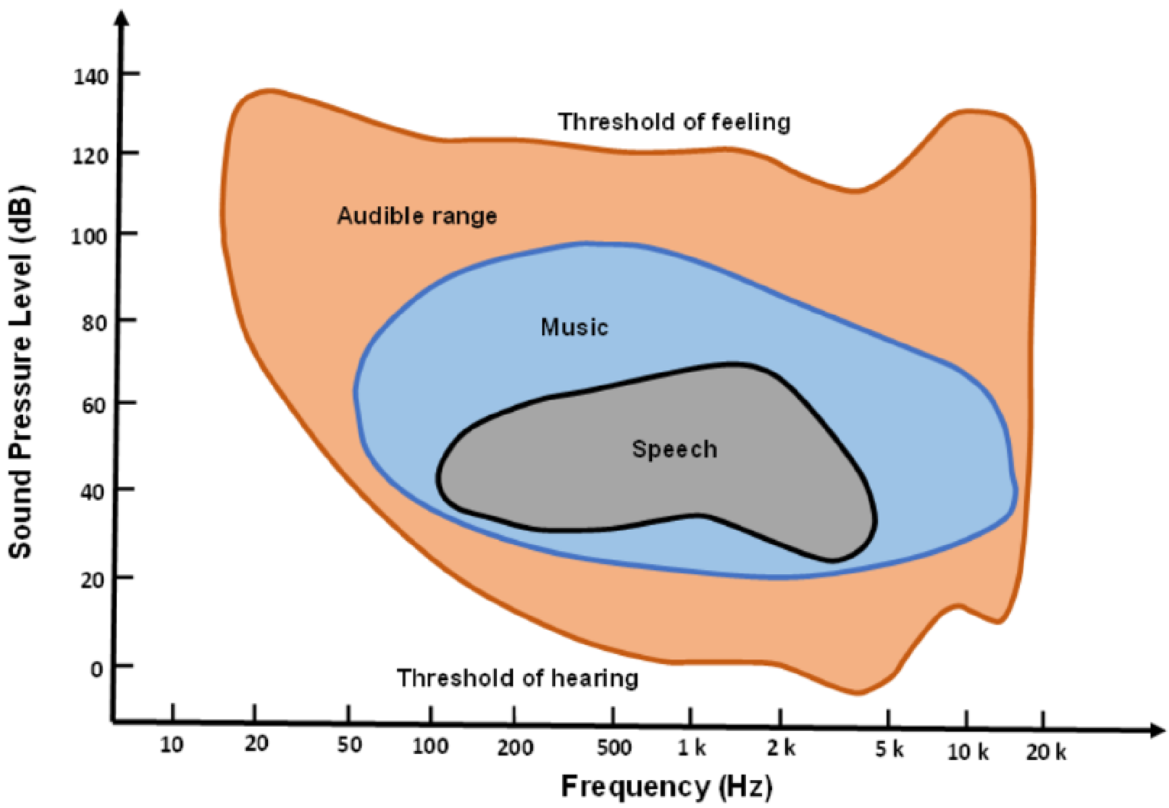

Figure 2.6: Audible Frequency Range for Humans

The audible frequency range for humans spans from 20 Hz to 20,000 Hz, divided into three general categories:

- **Low frequencies (<500 Hz):** These are associated with deep sounds such as engine vibrations, road noise, and structural resonances. Low-frequency sounds are more penetrating and can often cause discomfort or fatigue over prolonged exposure.
- **Mid frequencies (500 Hz–2 kHz):** This range includes much of the human voice and various environmental sounds. It is critical for clarity and intelligibility in audio signals and is often the focus in designing comfortable cabin acoustics.

- **High frequencies (>2 kHz):** These frequencies encompass sharp, high-pitched sounds like whistles, wind noise, and some mechanical components. While they are less dominant in automotive acoustics profiles, they can still contribute to occupant annoyance if not managed appropriately.

Sounds below 40 dBA are typically perceived as negligible or silent by human ears and often fall below the threshold of perceptibility in real-world environments. In automotive contexts, special attention is paid to sounds in the low-to-mid frequency ranges, as they often have the greatest impact on perceived comfort and fatigue. For these frequency ranges and in this case study, noise levels exceeding 40 dBA are generally considered intrusive and may compromise occupant satisfaction.

2.6 Sound Propagation

Sound propagates as a mechanical wave that requires a medium, such as air, water, or solid materials, to travel. The propagation of sound occurs in two main forms based on the characteristics of the medium:

- **Longitudinal waves:** These are the most common form of sound waves in fluids (gases and liquids), where particles oscillate in the same direction as the wave's propagation. This type of wave is responsible for the majority of audible sounds, as air primarily supports longitudinal sound waves.

- **Transverse waves:** Found primarily in solid materials, transverse waves involve particle oscillations that are perpendicular to the direction of wave propagation. These waves play a role in structural acoustics, particularly in analyzing vibrations and resonances in vehicle components.

The speed at which sound propagates is determined by the properties of the medium and can be expressed by the formula:

$$v = \sqrt{\frac{B}{\rho}}, \tag{2.3}$$

where:

- v: Speed of sound (m/s);

- B: Bulk modulus of the fluid (Pa);

- ρ: Density of the medium (kg/m^3).

Instead, the sound pressure level ($L_{p,A}$) at a receiver's location is influenced by the sound power level of the source (L_W) and attenuation factors (A) arising from sound propagation. The relationship is expressed as:

$$L_{p,A} = L_W - A, \tag{2.4}$$

where:

- $L_{p,A}$: Equivalent sound pressure level received (dB);

- L_W: Sound power level of the source (dB);
- A: Attenuation factors (dB) due to various factors, including distance, obstacles, reflections, and atmospheric conditions.

Sound propagation is described by standards such as ISO 9613, which provides methodologies for calculating attenuation factors associated with different propagation phenomena. These factors include:

- **Geometric divergence (A_{geo}):** Sound energy spreads out as it propagates, resulting in attenuation due to increasing distance from the source. This follows an inverse-square law for free-field conditions.
- **Atmospheric absorption (A_{air}):** Air absorbs sound energy, with attenuation increasing at higher frequencies. This factor depends on air temperature, humidity, and atmospheric pressure.
- **Ground absorption (A_{ground}):** The type of surface (hard, reflective, or absorptive) influences sound attenuation. Soft surfaces, such as grass or soil, absorb more sound, while hard surfaces reflect it.
- **Barrier attenuation ($A_{barrier}$):** Obstacles like walls or screens reduce sound levels by diffraction or absorption, particularly in the line of sight between source and receiver.
- **Miscellaneous attenuation (A_{misc}):** Factors such as vegetation or buildings contribute to additional sound attenuation.
- **Reflections ($C_{reflections}$):** Reflected sound waves from surfaces can increase sound levels at the receiver.
- **Meteorological effects (C_{meteo}):** Weather conditions, such as wind or temperature gradients, can refract sound waves, altering propagation paths.

The total attenuation is given by:

$$A = A_{geo} + A_{air} + A_{ground} + A_{barrier} + A_{misc} + C_{reflections} + C_{meteo}. \tag{2.5}$$

2.7 Vehicle Noise, Vibration, and Harshness

2.7.1 Noise Sources

The seat under examination is intended for installation in a sports vehicle homologated for road use. This implies that the seat must be lightweight, safe also in case of sudden acceleration, and comfortable enough for the driver and passengers to travel for hours, even on textured surfaces. From an NVH (Noise, Vibration, and Harshness) perspective, the vehicle is considered a system consisting of excitation sources, transfer paths, and receivers. Noise and vibration arise from various sources, all contributing to the overall experience. Carmakers dedicate significant efforts to mitigating their transmission into the cockpit to enhance passenger comfort. Unlike other aspects of vehicle performance, NVH is strongly influenced by human subjective perception; in fact, each human has is capacity to perceive the sound that is different from the others, because it depends on different factors like age, hearing health,... However, it is possible to identify the main sources of noise and vibration, to try to reduce as much as possible their influence. These sources can be split in three different classes:

- **Powertrain components:** These include the engine, transmission, and other drivetrain elements, which produce mechanical noise and vibrations propagating through the vehicle structure. Vibrations can result from combustion processes, unbalanced rotating components, or torque fluctuations, generating perceivable frequencies within the cabin.
- **Road interactions:** Tire-road noise and suspension-induced vibrations are major contributors to cabin noise. These sources originate from the interaction of the tires with uneven or textured surfaces, generating airborne and structure-borne noise transmitted through the chassis to the cabin.
- **Aerodynamic effects:** Wind noise becomes significant at higher speeds, caused by turbulent airflow over the vehicle's exterior, including areas around the windshield, side mirrors, and other design elements.

These noise sources are illustrated in Figure 2.7, where typical noise levels are shown in dB(A) to provide a quantitative understanding of their contribution to the overall NVH experience.

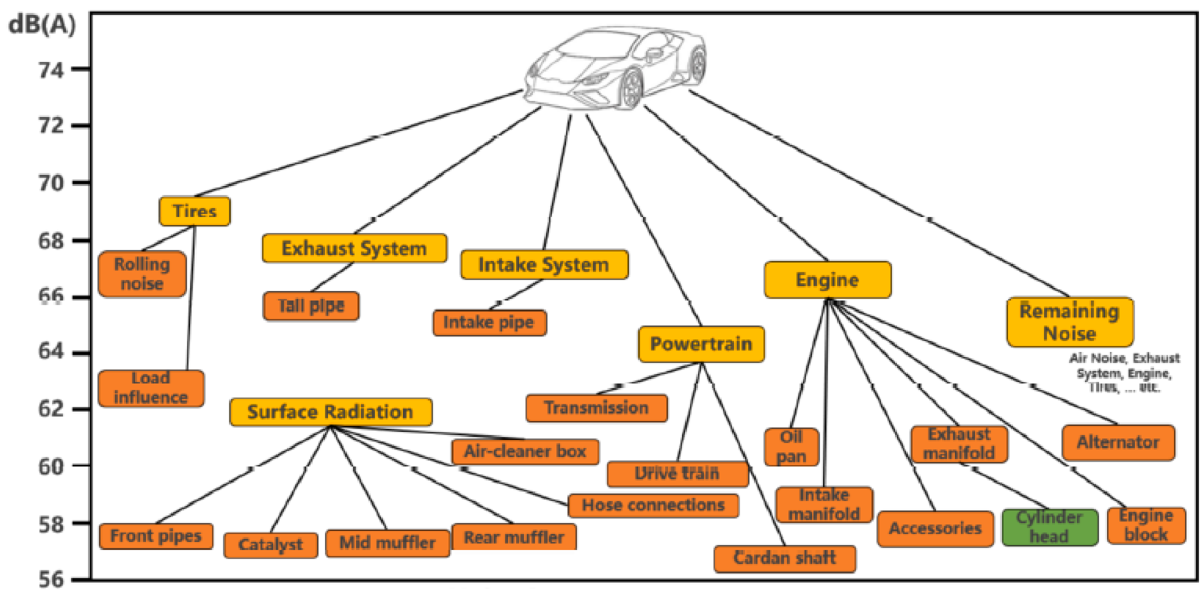

Figure 2.7: Vehicle's noise source ranking

2.7.2 Noise Contribution at Different Speeds

The overall noise profile of a vehicle is shaped by a complex interplay of various noise sources, whose contributions vary significantly depending on the vehicle's speed and operating conditions, as shown below in Figure 2.8.

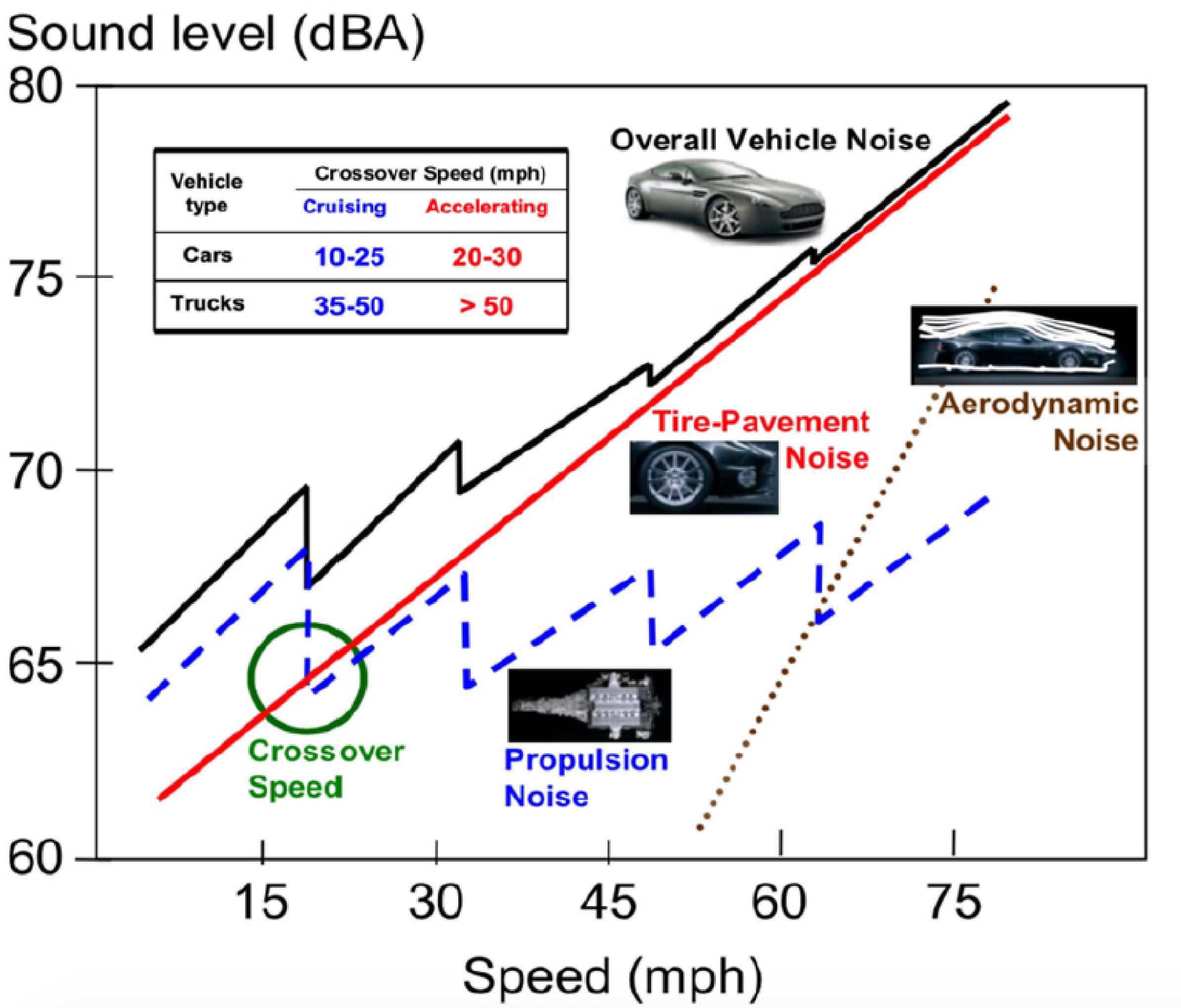

Figure 2.8: Vehicle noise components versus speed

At lower speeds, **propulsion noise**, mainly generated by the engine, transmission, and exhaust system—tends to be the dominant source of sound. This noise is particularly noticeable during urban driving or when the vehicle is accelerating. As the vehicle's speed increases, tire-pavement interaction noise becomes more prominent. This noise originates from the physical contact between the tires and the road surface and grows more significant at moderate to high speeds, especially on rough or uneven roads, where it substantially contributes to the overall cabin noise levels. **Aerodynamic noise** becomes a critical factor at higher speeds. It is generated by turbulent airflow around the vehicle's body and is affected by factors such as the vehicle's shape, the design of protuberant elements like side mirrors and roof racks, and the sealing quality of door gaps and window edges. Unlike propulsion and tire-pavement noise, which dominate at specific speed ranges, aerodynamic noise becomes a significant factor only at speeds exceeding approximately 100 km/h, where it can cover other noise sources in intensity. The evolution of vehicle design and the transition toward electric powertrains are reshaping the relative importance of these noise sources. For instance, the quieter operation of electric motors has greatly reduced propulsion noise, highlighting the need to address tire-pavement and aerodynamic noise to maintain a refined and comfortable driving experience.

2.7.3 Transmission of Noise and Vibrations to the Cockpit

Once the different sources of noise are clear, it is important to focus on the way in which the occupant perceived the vibrations and noises through the vehicle interior. They propagate through different pathways and manifest as either **structure-borne noise** or **airborne noise**, each of which has distinct transmission mechanisms and mitigation strategies.

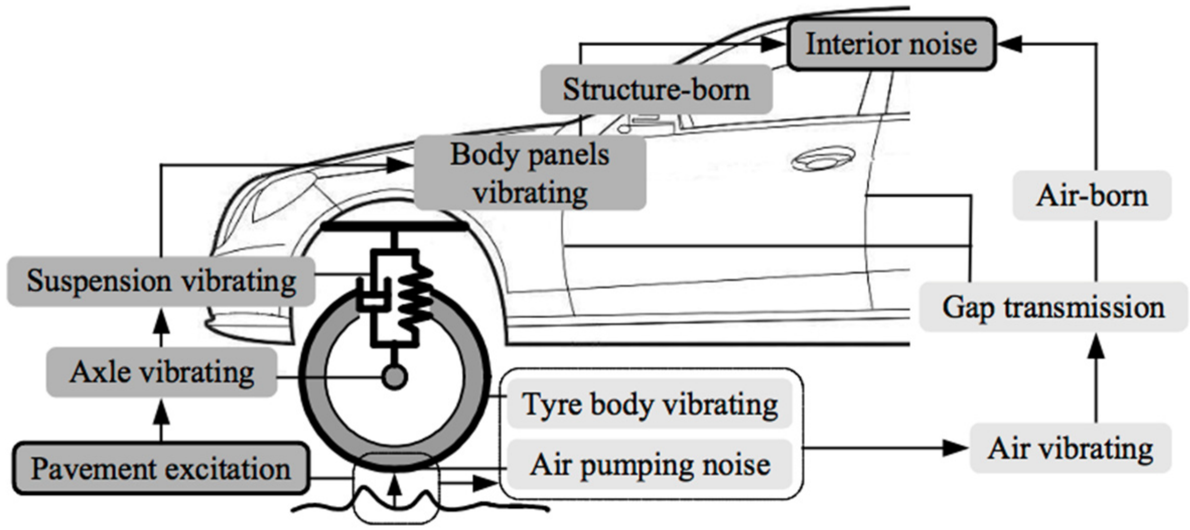

Figure 2.9: Vehicle interior noise transmission path

Structure-Borne Noise

Structure-borne noise refers to vibrations generated by external forces that travel through the vehicle's rigid components, such as the chassis, suspension, and body structure, before reaching the seat. This type of noise is typically low-frequency and is caused by:

- **Road-Induced Vibrations:** Uneven road surfaces and speed bumps create vertical and longitudinal forces on the tires, transmitted through the suspension system and vehicle frame to the seat structure.
- **Powertrain Vibrations:** Engine firing pulses, drivetrain imbalances, and transmission operations introduce vibrations that propagate through mounts and structural components.
- **Resonances:** The vehicle body and seat frame have natural frequencies that may amplify structure-borne vibrations when excited by certain frequencies.

Airborne Noise

Airborne noise is generated by sound waves traveling through the air before reaching the seat and occupants. Key sources include:

- **Engine and Exhaust Noise:** Airborne sound waves produced by these components can penetrate the cabin, especially if insulation is inadequate.

- **Aerodynamic Noise:** Turbulent airflow around the vehicle body, mirrors, and seals generates high-frequency noise that infiltrates the cabin, often becoming dominant at highway speeds.
- **Tire-Road Interaction Noise:** Although primarily structure-borne, tire-pavement interactions can also produce airborne sound waves, especially at higher speeds.

Airborne noise transmission to the seat is influenced by the cabin's acoustic insulation, the sealing quality of windows and doors, and the damping properties of interior materials.

Airborne vs. Structure-Borne Noise: Importance for Seats

Both airborne and structure-borne noise affect occupant comfort, but structure-borne noise tends to have a more direct impact on seats. This is because it is mechanically coupled to the vehicle's vibrating components, such as the chassis and suspension.

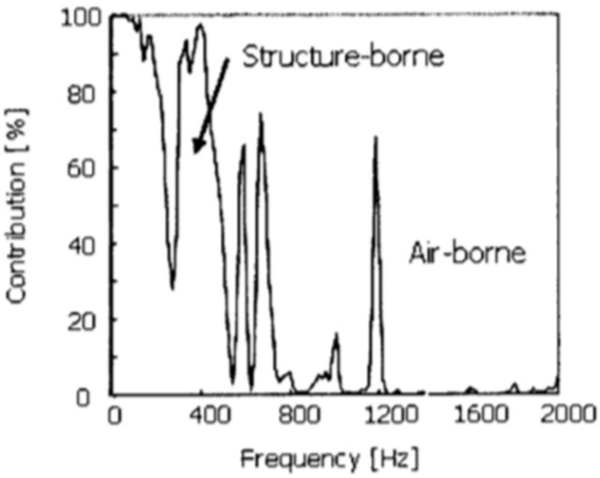

Figure 2.10: Contribution of tire structure-borne and airborne noise for interior noise

However, airborne noise, including wind or engine sounds, should not be neglected. These sounds, if not adequately mitigated, can degrade the cabin environment and contribute to a perception of poor quality. Effective insulation, combined with materials that absorb or reflect sound waves, is essential to mitigate this type of noise.

2.7.4 Transmission Pathways to the Seat

The seat in a vehicle represents the critical interface between the occupant and the various noise and vibration sources originating from external excitations. As it is seen before, the transmission of these disturbances to the seat occurs through multiple pathways, each with distinct characteristics and implications for comfort and NVH performance.

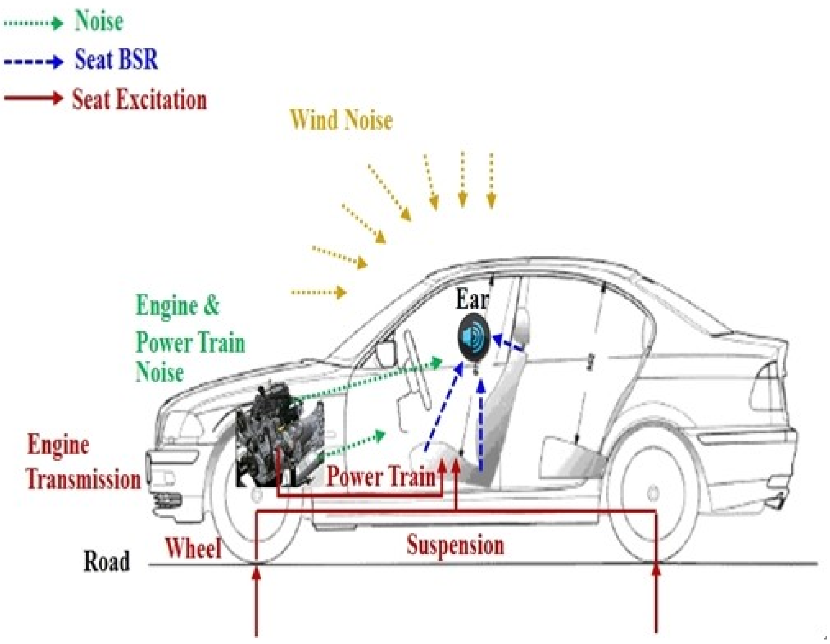

Figure 2.11: Transmission Pathways to the Seat

Vibrations generated by the vehicle frame, floor pan, or seat rails are mechanically transmitted to the seat structure, and this transmission is significantly affected by the damping quality and the stiffness of the connections. For example, rigid connections can intensify vibrations, making them more perceptible to the occupant. Another critical pathway for vibration transmission is the suspension system, which transfers road-induced vibrations to the chassis. The forces arising from tire-road interactions, especially on uneven surfaces or during dynamic maneuvers, travel through suspension components and reach the seat via the floor structure. While the suspension system helps to isolate some vibrations, it can also transmit others, particularly in the low-frequency range, where human sensitivity to vibrations is heightened. In addition to mechanical vibrations, airborne noise contributes to the occupant's acoustic experience. Sound waves from internal or external sources, such as the engine, exhaust system, or turbulent airflow, travel through the cabin air and interact with the seat surfaces. These sound waves cause pressure fluctuations that are perceived as noise by the occupants. The transmission of airborne noise is influenced by the cabin's acoustic insulation and the material properties of the seat. Lastly, the seat frame itself can amplify vibrations through resonance. Like any structural component, the seat frame has natural frequencies where it tends to vibrate more intensely when excited. If these resonant frequencies align with external vibration frequencies, the seat may amplify disturbances rather than dampening them, further affecting occupant comfort.

Chapter 3

Power Spectral Density

The Power Spectral Density (PSD) is widely used to characterize the distribution of a signal's power across different frequencies, and it is a fundamental concept in signal processing. PSD represents the frequency-domain counterpart of a time-domain signal, and it is helpful to understand how energy is distributed in a signal. When comparing time-domain with frequency-domain analysis, what is changing is the focus on the output signal. Precisely, time-domain analysis focuses on how signal values vary over time, while PSD shifts the perspective to reveal how energy is distributed across frequency bands. This is particularly useful in analyzing systems as the one depicted in this case study, where random vibrations (that simulate a real-word road) are used as input to a mechanical system (mono-axial shaker linked through a structure to the seat).

3.1 Technical Definition

In continuous time, the PSD of a stationary random process $x(t)$ is defined as the Fourier Transform[2] of its Autocorrelation Function $R_x(\tau)$[3]. The autocorrelation function $R_x(\tau)$ describes the correlation between the signal and its delayed version over a time shift τ, capturing how the signal behaves over time. The PSD, denoted as $S_x(f)$, quantifies how power is distributed across different frequencies. Mathematically, the PSD can be expressed as:

$$S_x(f) = \int_{-\infty}^{\infty} R_x(\tau) e^{-j2\pi f\tau} \, d\tau, \tag{3.1}$$

where:

- $R_x(\tau) = \mathbb{E}[x(t)x(t+\tau)]$: Autocorrelation function, measuring similarity between the signal at time t and a delayed version at $t+\tau$.
- $S_x(f)$: Power Spectral Density as a function of frequency f, indicating how the signal's power is distributed across frequencies.
- f: Frequency (Hz) at which power is evaluated.
- j: Imaginary unit, accounting for the complex nature of frequency components.

PSD is commonly used for stationary random processes, where statistical properties (e.g., mean and variance) remain constant over time. For a vibration signal, PSD units are typically g^2/Hz (where g is acceleration due to gravity), representing vibrational power in each frequency band.

3.2 PSD Profile for This Case Study

The PSD defines the frequency distribution of the input signal. In automotive seat testing, this signal typically includes low-frequency content (e.g., < 10 Hz) from body motion and chassis vibration, as well as higher frequencies (e.g., 10–100 Hz) from suspension and wheel-induced vibrations. The PSD's role is to quantify this distribution so that the shaker system can replicate it precisely during testing.

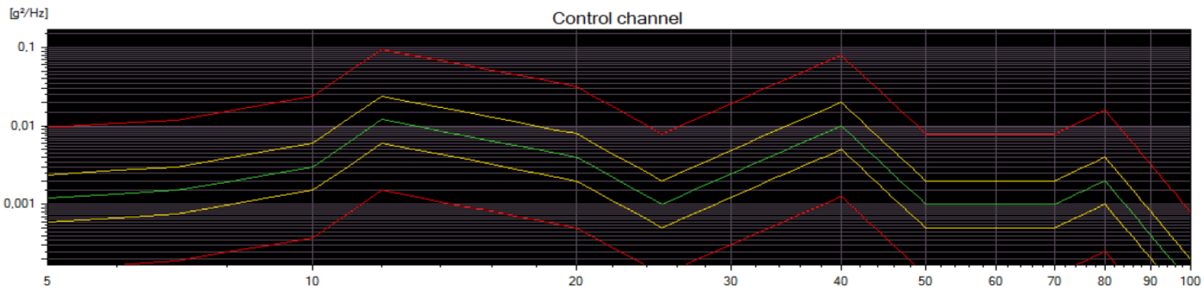

Figure 3.1: Real-time feedback control systems

The Figure 3.1 represents the Power Spectral curve that is designed based on the target vibration profile to replicate, which could correspond to real-world conditions like road-induced vibrations and it is chosen by the customer. Given that various road conditions impose different types of stress on a vehicle, the PSD input signal is designed to replicate these different excitations. Each profile corresponds to a specific acceleration pattern, and in this case study, the "sport profile" is used as the input. This profile represents the most demanding scenario, ensuring that if the seat can withstand and perform under these conditions, it will also be capable of meeting the requirements of less challenging profiles. The shaker must be carefully controlled to match the input PSD, ensuring that both the frequency content and power levels are accurately replicated. Real-time feedback control systems adjust the shaker's amplitude at different frequencies to match the specified PSD. This approach ensures that the excitation is consistent over time and accurately represents the natural environment the seat would face.

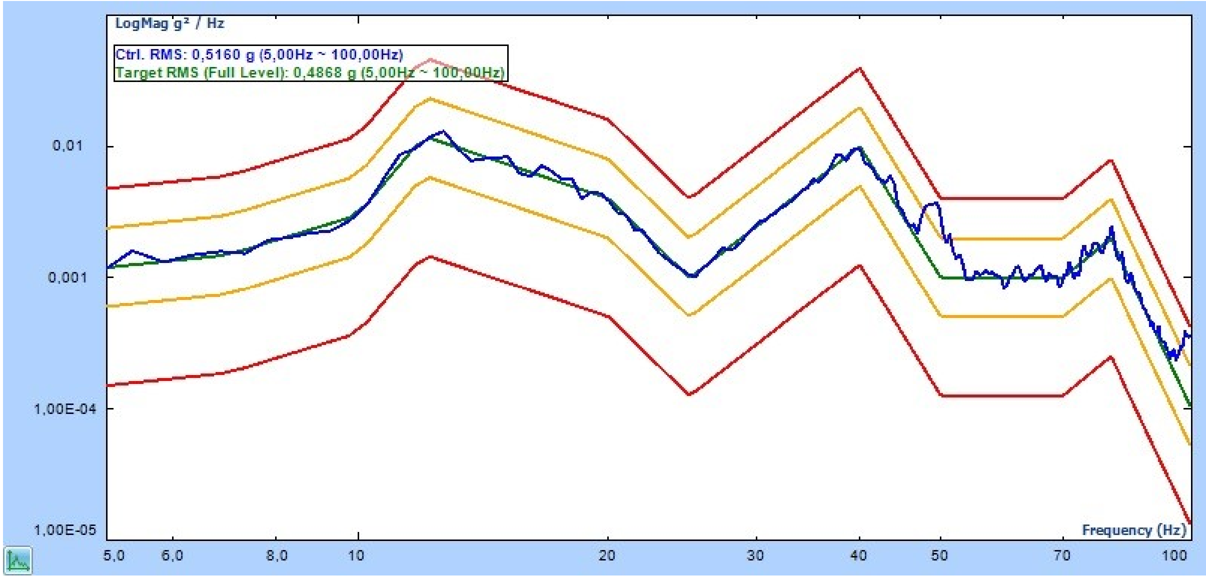

Figure 3.2: PSD

The Figure 3.2 displays the output from the Engineering Data Management (EDM) system software, showcasing the real-time feedback of the PSD applied as input across all frequencies. As observed, the Power Spectral Density signal closely aligns with the input, remaining consistently within the predefined limit range (indicated by the red curve).

3.3 Other PSD Applications

There are different types of Power Spectral Density (PSD) profiles used for various testing purposes. The PSD used as input in this case study is the "Sport Profile," which is relatively severe, but it accurately represents a real-world scenario. It simulates the vibrations that a seat would experience during high-stress conditions, such as when the vehicle is driven on rough or uneven roads and is therefore considered one of the most demanding real-world test conditions. So, if the seat is able to pass this test, the others that are more conservative are surely passed. However, there are also PSD profiles used for fatigue testing that are not reported because these kinds of simulations are made only to help to identify and isolate the exact component or area of the seat that is responsible for the noise generation. These profiles are specifically designed to practically see how a precise component could danger the seat if the noise phenomena are prolonged for a while. In fact, there are no norms that regulates these tests and usually the noise is not recorded and not shared with the customer. For these types of tests, a specific acceleration at a particular frequency is selected, and a sweep is performed over time to assess the seat's response under continuous vibration. This method allows for a focused analysis of the seat's behavior at a particular frequency and acceleration, identifying how the seat handles specific vibrational conditions over extended periods. During these tests, particular attention is given to the sources of any noise generated, and the impact on the seat's components is analyzed to understand where the noise originates and what causes it.

Chapter 4

System Instruments Description

In this chapter, all the components and equipment utilized to conduct the vibrational seat test are presented and described in detail in order to offer a comprehensive understanding of the tools, devices, and methods used to simulate conditions required for analyzing the car seat's vibrational behavior. This includes test equipment such as the mono-axial shaker, sensors to measure vibrations and sound pressure levels, and data acquisition systems to ensure precise recording and interpretation of results. Additionally, the test environment configuration, particularly the semi-anechoic chamber, which is crucial for isolating external noise and vibrations, is seen. Each component is introduced with an explanation of its specific role in the test setup, clarifying how the system operates cohesively to simulate real-world vibrational conditions and evaluates seat performance.

4.1 Anechoic Chamber

Figure 4.1: Sabelt Anechoic Chamber

The semi-anechoic chamber at Sabelt depicted in Figure 4.1 is specifically designed to isolate external noise and vibrations, offering a controlled environment for reproducible testing. Thick insulated walls and vibration-damping materials effectively block external disturbances, while sound-absorbing panels lining the interior to eliminate reflections, simulating a free-field acoustic condition. The floor is also isolated from the vibrations, ensuring consistent and reliable results during dynamic testing. The chamber complies with key standards, including **UNI EN ISO 3382-2**, **UNI EN ISO 3744**, and **UNI EN ISO 11957**, which collectively validate its suitability for precise acoustic measurements. The **UNI EN ISO 3382-2** standard ensures low reverberation times within the chamber, confirming its ability to minimize sound reflections and isolate noise effectively. Compliance with **UNI EN ISO 3744** guarantees that the chamber supports accurate sound power level measurements in a controlled acoustic setting. The **UNI EN ISO 11957** standard further defines the chamber's capacity for detailed acoustic assessments of individual seat components that may contribute to noise issues. By adhering to these standards, the chamber guarantees that the testing results are both accurate and reliable. The controlled environment allows technicians to reproduce tests consistently, enabling direct comparisons between modified seats without the influence of external factors, thereby supporting precise and effective noise and vibration evaluations.

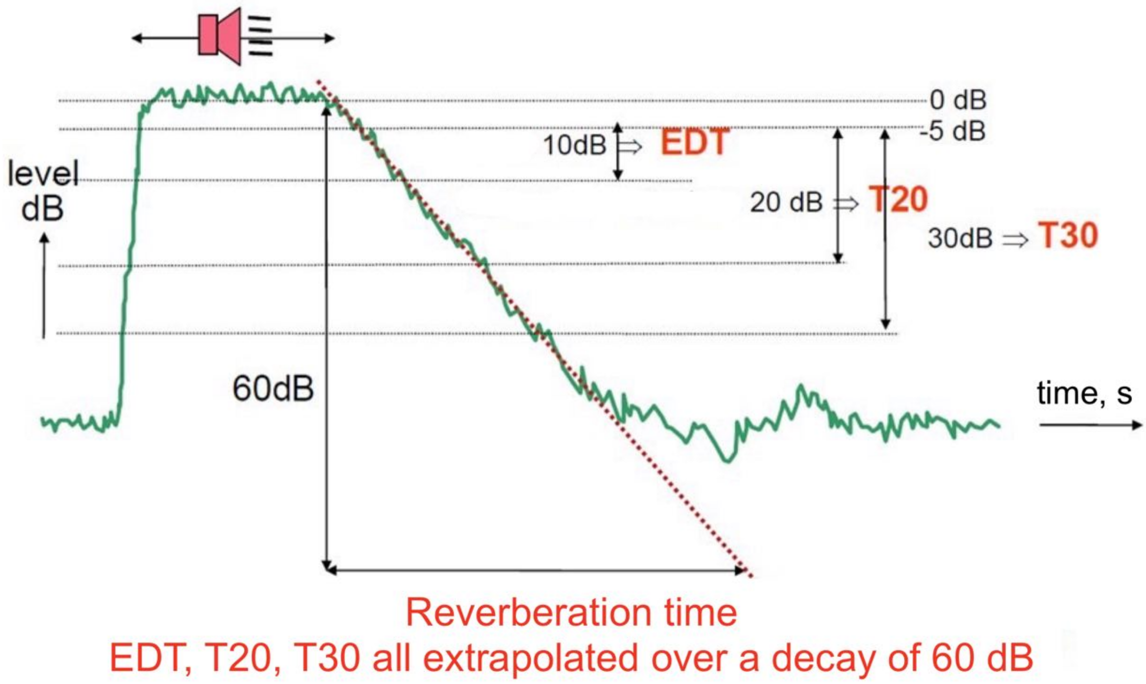

Figure 4.2: Reverberation Decay Curve

The Figure 4.2 depicts the reverberation decay curve and highlights key acoustic parameters such as the initial decay time (EDT), T20, and T30. When a sound source is turned off, the sound energy starts to decay. The initial decay time (**EDT**) is the time it takes for the sound level to decrease by 10 dB, marking the onset of the sound absorption process. This parametes represents the initial portion of the decay curve and play an important role for evaluating how quickly the chamber begins to absorb sound after the source stops emitting. The decay curve also includes **T20** and **T30**, which denote the time required for the sound to decay by 20 dB and 30 dB, respectively. These values are essential for understanding the overall behavior of sound decay within the chamber and are commonly used to quantify sound absorption over longer periods. In the anechoic chamber used for this case study, these decay times are minimized. The chamber's ability to achieve low **EDT**, **T20**, and **T30** values ensures that sound reflections and reverberations are effectively suppressed, enabling precise measurements of noise and vibrations generated by the seat. The chamber's volume is important to ensure that sound waves can dissipate without encountering reflective surfaces during the short path between the emission point (the tested seat) and the measuring instruments, such as microphones and accelerometers. Insufficient chamber size can lead to high-energy sound waves, specially low-frequency ones, may not be fully absorbed before reaching the walls, leading to reflections that could affect measurements accuracy. The use of an anechoic chamber is driven by the need to mantain low **reverberation time (RT)** and **initial decay time (EDT)**. This approach ensures that test results accurately reflect the true sound and vibration characteristics of the seat without interference from the chamber acoustics or external noise. The combination of low decay values and sufficient chamber volume isolate the vibrations of the seat under test, simplifying the analysis of how vibrations propagate through the seat and the translation into cabin noise.

4.2 Mono-axial Shaker (Model m120Q/MA1-CE)

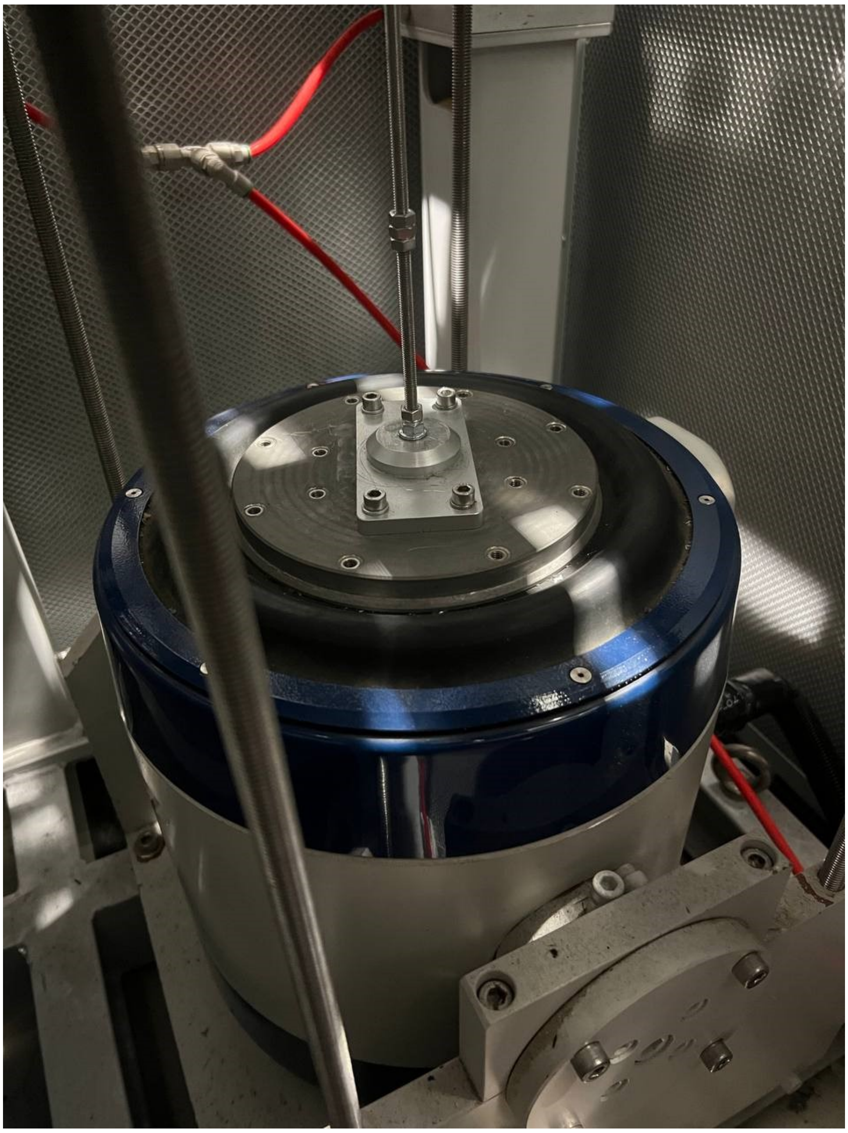

Figure 4.3: Mono-axial Shaker

The mono-axial shaker (**Model m120Q/MA1-CE**), depicted in Figure 4.3, is a precise instrument designed to replicate real-world vibration conditions along a single axis. It operates using an electromagnetic drive system that generates vibrations through the interaction between a magnetic field and an electrical current. This system allows precise control over vibration key parameters such as frequency, amplitude, and acceleration, making the shaker ideal for replicating specific excitation profiles including the **Power Spectral Density (PSD)** curves used in this case study. The shaker produces a controlled and consistent force and it is suitable for medium-duty applications. Its wide frequency range allows it to simulate various scenarios, from low-frequency vibrations caused by road surfaces to high-frequency excitations resulting from engine harmonics. The frequency range required by the PSD profile in this case study is fully covered by the capabilities of the shaker used at Sabelt, ensuring accurate and reliable testing.

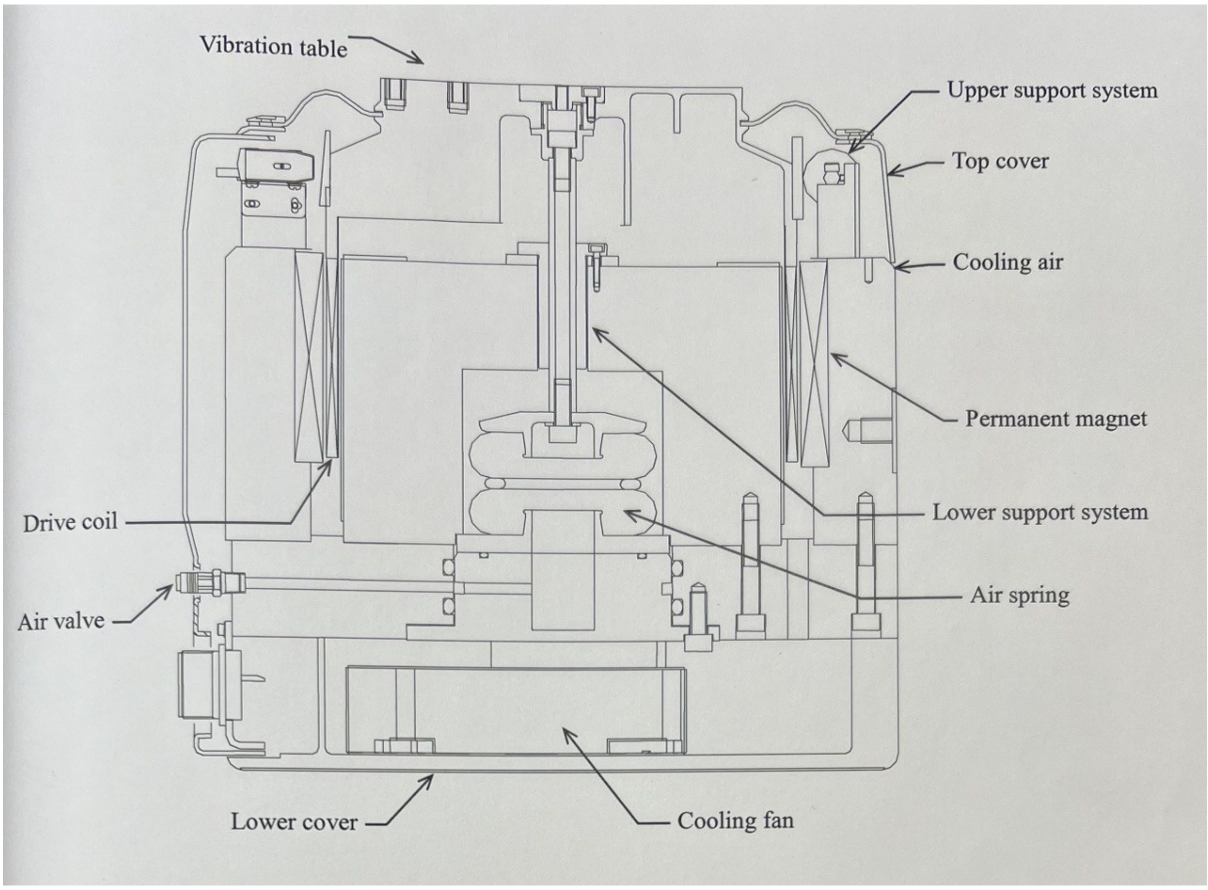

Figure 4.4: Technical diagram of a vibration shaker

Figure 4.4 presents a detailed the diagram of the mono-axial shaker, with all the components labeled and identified by name. Central to its operation is the moving coil assembly, which converts electrical energy into mechanical motion. This assembly is supported by upper and lower stabilization systems that minimize distortion and keep vibrations constrained to the vertical axis. The shaker also employs a low-friction bearing or flexure system that reduces wear and ensures durability during extended and high-power testing. To improve the precision of the tests, the shaker is equipped with a vibration table where the seat is fixed. This table prevents the transmission of unwanted vibrations,mantaining controlled conditions throughout testing. Additionally, the system's low noise emissions is a characteristic that reduces interference from external sounds during testing. Thermal protection mechanisms, including cooling systems, are integrated into the shaker to dissipate heat generated during high-power operations, enabling consistent performance, even in prolonged testing sessions. Safety measures, such as displacement limiters, protect both the shaker and the test specimen from potential mechanical damage. The design of the shaker focuses vibration energy along the vertical axis, effectively reducing interference from other directions and ensuring that test conditions are precisely aligned with the desired input parameters.

4.3 Engineering Data Management (EDM) System

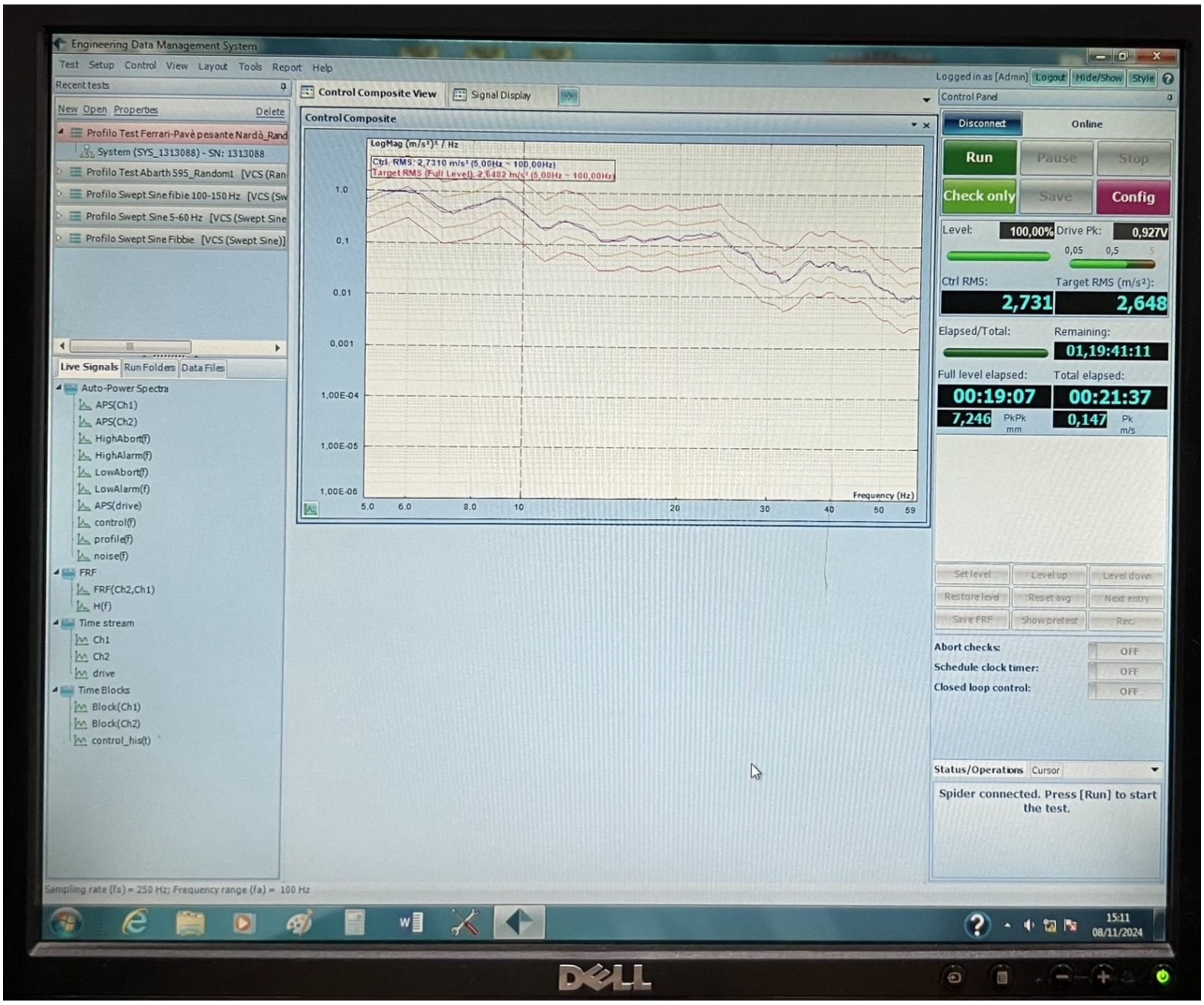

Figure 4.5: EDM System

The Engineering Data Management (**EDM**) system used in the Sabelt laboratory is as a centralized platform used to manage and organize all data generated during tests, ensuring both accessibility and traceability throughout the project lifecycle. During the tests, the **EDM** system stores **Power Spectral Density (PSD)** input feedback signals, time-history recordings, and results from an objective points of view, enabling comparisons between various test conditions. Additionally, the **EDM** system saves changes made to structural adjustments or seat modifications. Each iteration's results are recorded, ensuring that data from different testing phases can be efficiently reviewed and compared each with the other, ensuring consistency throughout the testing and development process.

4.4 Power Amplifier and Vibration Controller

Figure 4.6: Power Amplifier and Vibration Controller

The amplification of the input signal from the test control system is one of the primary functions of the integrated amplifier, precisely, the **Power Spectral Density (PSD)** curve defined earlier. The shaker's electromechanical system requires a significant amount of power to generate the necessary vibrations, meaning that the signal must be boosted to a level sufficient to drive the system effectively. However, the amplifier not only boosts the signal but also ensures the integrity of the signal is preserved throughout the amplification process. A key feature of the **Vibration Controller** is its closed-loop feedback control system. This system constantly compares the shaker's output with the desired input signal and adjusts the amplification as needed to correct any discrepancies. This ensures that the excitation received by the seat remains within the limits defined by the **PSD profile**. The amplifier is also equipped with thermal protection mechanisms to prevent overheating during extended operation. In fact, when temperatures exceed safe limits, the output power is automatically reduced to ensure safe and consistent performance.

4.5 Microphone Bruel & Kjaer (B&K 4189)

Figure 4.7: B&K 4189 Microphone

The microphone used in this case study is specifically designed to measure sound pressure in open environments free of reflections, making it ideal for use in the semi-anechoic chamber. With an extended frequency response ranging from 20 Hz to 20 kHz, the microphone is capable of capturing sound across a wide spectrum, from low to high frequencies. The **B&K 4189** microphone is known for its high sensitivity. In fact, it is especially effective for measuring low-level sounds. It captures audio without introducing coloration or distortion across its operational range. This precision is essential for generating objective and reliable test results. To maintain its accuracy, the microphone is used in conjunction with a calibration device (**BRUEL & KJAER TYPE 4231**), that ensures that the microphone remains properly calibrated, providing consistent measurements for customer reporting and analysis. Before of starting the noise measurements of all the cases, it is important to measure the background noise and the noise emitted by the test bench during its operation, so that, once the seat will be fixed on the test bench, it will be possible to eliminate these noises that could alter and compromise the final result.

4.5.1 Microphone positioning during measurements

Another important aspect to consider is the position of the microphone in function of the H point (theoretical point that represents the position of the driver's or passenger's hip when seated). The microphone can be positioned in different points in function on where the noise sources are. In fact, in Sabelt laboratory, there are three main positions:

- **Noise measurement in frontal backrest area:** 500 mm in Z axis respect to the H point, and in Y axis on the center line of the seat. This case is used to measure noise coming from Headrest, Anti-whiplash system/Lumbar adjustment and Sidebag.

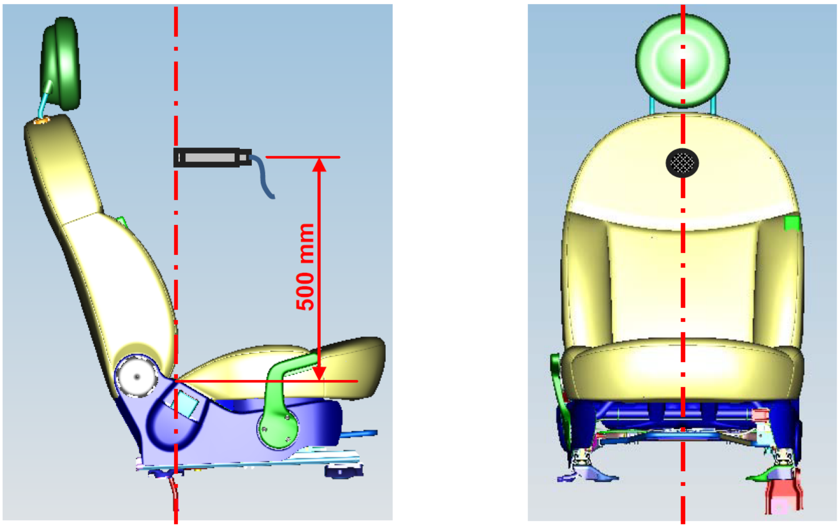

Figure 4.8: Microphone in frontal backrest area

- **Noise measurement in the lower left/right side area:** 100 mm in Y axis from the left/right edge of the seat respect to the H point. This case is used to measure noise coming from Recliner and Plastic covers, and the microphone will be positioned on the side where the noise is generated.

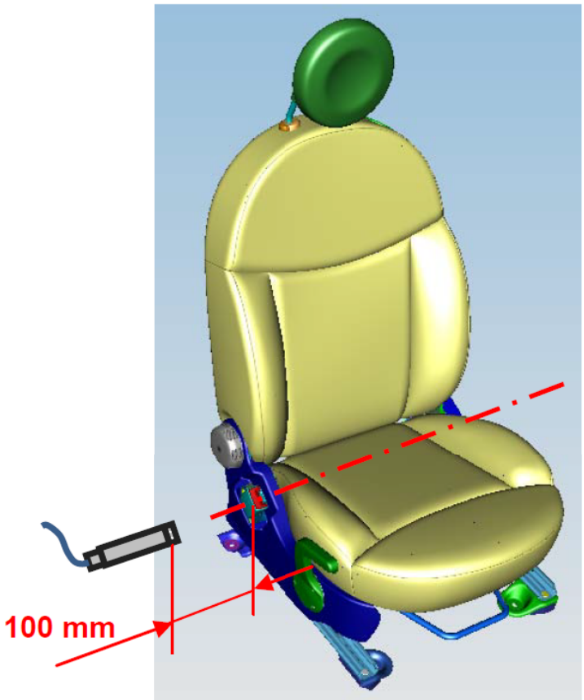

Figure 4.9: Microphone in the lower left/right side area

- **Noise measurement in the lower frontal area:** 100 mm in X axis respect to the closest point in this direction and 100 mm in Z axis respect to the guide frontal attachment point. This case is used to measure noise coming from Seat rails, Lift mechanism, Guide release bracket.

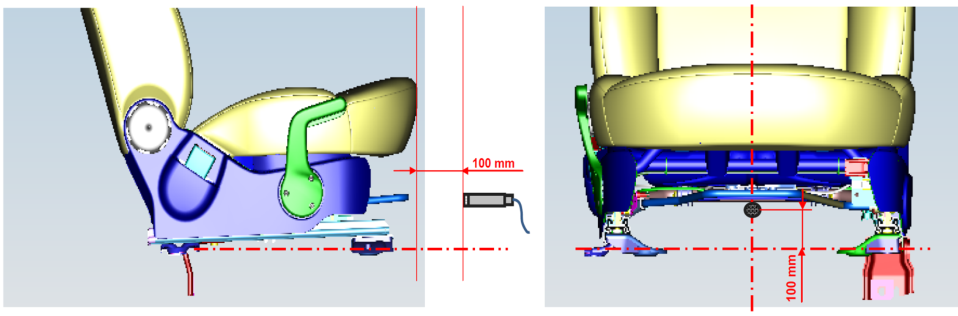

Figure 4.10: Microphone in the lower frontal area

For all measurements conducted in this project, specifically during the noise assessment of different configurations, the **frontal backrest area** is chosen as the measurement position. This choice is made because this is the closest point to the occupant ears that catch the noise generated by the seat. In this way, the measurement accurately represents the real user experience by capturing the sound as it would be heard in a typical seating position.

Chapter 5

Shaker-Based Driving Simulator

Figure 5.1: Case Study Seat

The Figure 5.1 represents the seat that is analyzed in this case study. The necessary vibrational inputs are transmitted to the seat using a vibration test bench containing a shaker. The input is controlled with a signal generator and a dedicated software to accurately reproduce the PSD. Microphone, analyzer, and recorder are other tools used to capture and analyze the noise responses of the seat. This test is made inside of an anechoic chamber to avoid that external noises interfere with the results, compromising the test itself.

5.1 Vibrational Seat Test

A Power Spectral Density (PSD) signal is used as input to the vibrational test bench equipment. This signal, which it is provided by the customer, accurately reproduces the vibrations that are transmitted in a vehicle during dynamic conditions so that the seat evaluation reflects conditions that represents real-world usage. The testing process begins with the seat that is well fixed on the test bench. The seat is mounted trying to replicate its configuration in a vehicle. Once the seat is correctly installed, the accelerometric signal that simulates vibrations encountered during heavy road conditions are given as input to the software that create a signal and transmit it to the shaker. The vibrations, in the profile chosen by the customer, are applied for a duration of ten minutes under heavy usage condition to ensure that the simulated real road matches the accelerations given as input to the shaker. During the test, both subjective and objective evaluations are performed. For the Subjective evaluation, experienced technicians fill a standardized scale shown in table 5.1 to evaluate the noise produced by the seat. This method accounts for the human perception of noise, and the high experience of the technicians is very important to give a concrete result. Simultaneously, objective measurements are conducted by recording the noise emitted by the seat and comparing it with the noise limit profile. The data is recorded in a detailed way and it is later analyzed to identify peaks, patterns, and potential areas that cloud cause the noise. The results of these tests are then compared with the standards and with the specific requirements outlined by the customer that want a precise comfort of their seat. This comparison is useful to understand if the seat needs some modification and, by analizing the frequency spectrum, what kind of modification could consider to be applied. In cases where anomalies are detected, adjustments are proposed by the technicians of the Sabelt laboratory in collaboration with the engineering area to reduce the noise causes. The most famous solutions may include changes in design, materials, or manufacturing processes to enhance the seat's performance and improve its comfort.

5.2 Regulatory Standards

Human are sensitive to various ranges of vibration and noise. Each human has its capacity to perceive in a different way such quantities like sound and noise, in fact, an objective relationship between vibration and noise and some NVH performance index is difficult to assess, specially if it is trying to make the evaluation as less subjective as possible. In fact, at the end of the test, expert technicians in the field are compiling a SAE rating scale, such as the one shown in the table below. This scale is used to evaluate the levels of noise or vibration that are perceived by the occupants based on the technician's subjective experience, which reflects how the occupant feel these noises in real-world conditions.

		UNACCEPTABLE				**ACCEPTABLE**					
CUSTOMER VIEWPOINT	Judgment	Very poor	Poor	Less than mediocre	Mediocre	Acceptable limit	Acceptable	Discreet	Good	Very good	Excellent
	Detectability	All customers	Medium customers			Critical customers		Expert customers			
	Perceptibility	**HIGH**			**MODERATE**			**SMALL**		**VERY SMALL**	**NONE**
	Sensation	Intolerable		Strong discomfort	Discomfort	Slight discomfort	Small disturbance		Minimal disturbance	No disturbance	
	Reaction	Refusal		Protest		Complaint	Acceptance		Appreciation		Enthusiasm
Alphanumeric scale	**Voting Scale (1-10)**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Corrective Actions		Radical and immediate intervention		Timely corrective intervention			To be improved	Requires attention		OK	

Figure 5.2: SAE Rating Scale

The goal of this scale is to helps categorize the intensity of vibrations and noise. This standardized framework aims to objectively interpret the subjective experience of comfort and operation when components are tested. The chart can extend from "unacceptable" to "acceptable", with gradations in between representing fluctuating degrees of intensity or comfort.
The specific levels describe the noise or vibration's intensity, such as:

- **Unacceptable:** The noise or vibration is perceived as disturbing, uncomfortable, or outside acceptable operational standards.
- **Acceptable:** The noise or vibration is within tolerable limits and does not affect the comfort or safety of the occupants.

However, an objective evaluation of the tests is obtained by making reference to the acceptability limit shown in Figure 5.3

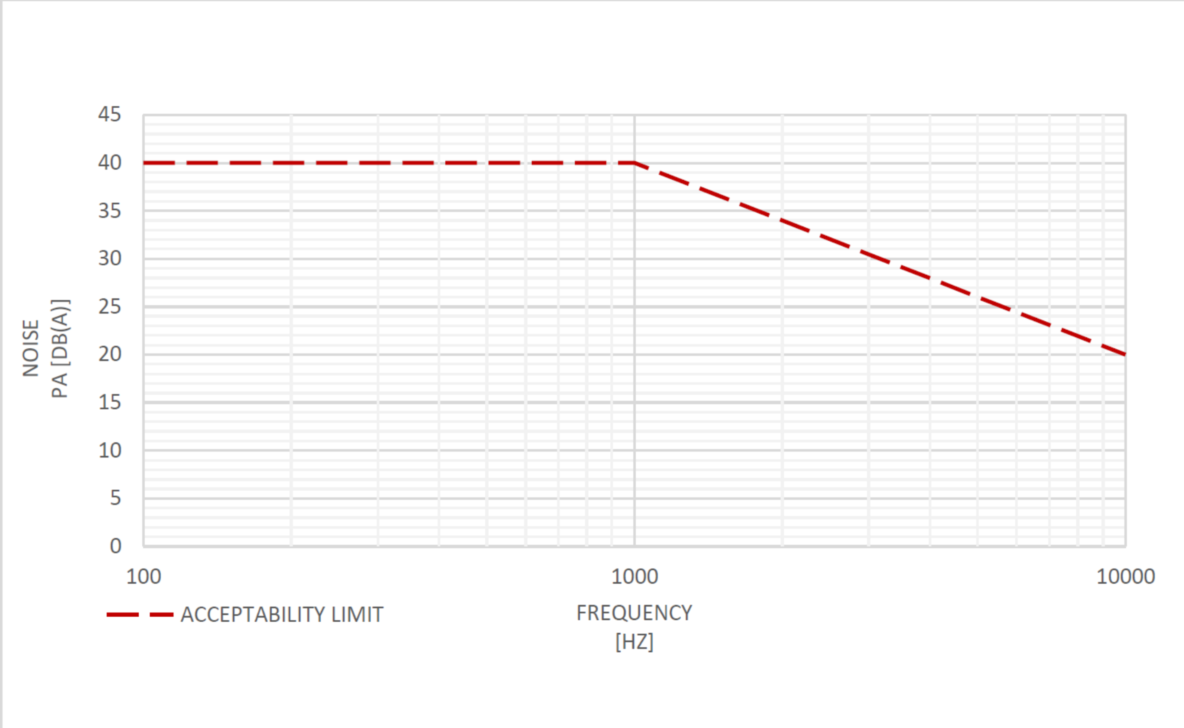

Figure 5.3: Acceptability Limit

The acoustic target is defined by the acceptability limit shown in the figure. The x-axis shows the frequency range in which the seat has to be analyzed while the y-axis indicates the noise intensity measured in decibels (dBA). The noise curve represents the noise emitted by the component of the seat and if it exceeds the acceptability limit curve in terms of noise intensity, the seat is considered to be out of specification. The acceptability limit is determined based on specific norms (7-N5181), indicating the maximum noise level that the component can emit without causing discomfort to the occupant if mounted on a vehicle. If the noise emission at any frequency range exceeds the defined limits, corrective actions may be necessary to some components of the seat to achieve a more acceptable noise performance, as it is done in this case study.

5.3 Optimizations

In order to pass the tests and achieve favorable results in compliance with both the specified standards, several modifications were made to the seat in the laboratory. The modifications focused on optimizing various aspects of the seat's design and functionality, for example its structural components or its attachment mechanisms. The purpose of these optimizations is to improve the seat performance ensuring that it met the required specifications. This section will provide a detailed overview of each modification made, explaining the reasoning behind the changes and the how each modification should improve the seat in terms of rigidity, stability and frictions characteristics.

5.3.1 Reduced-Play Guides with 7 daN Load

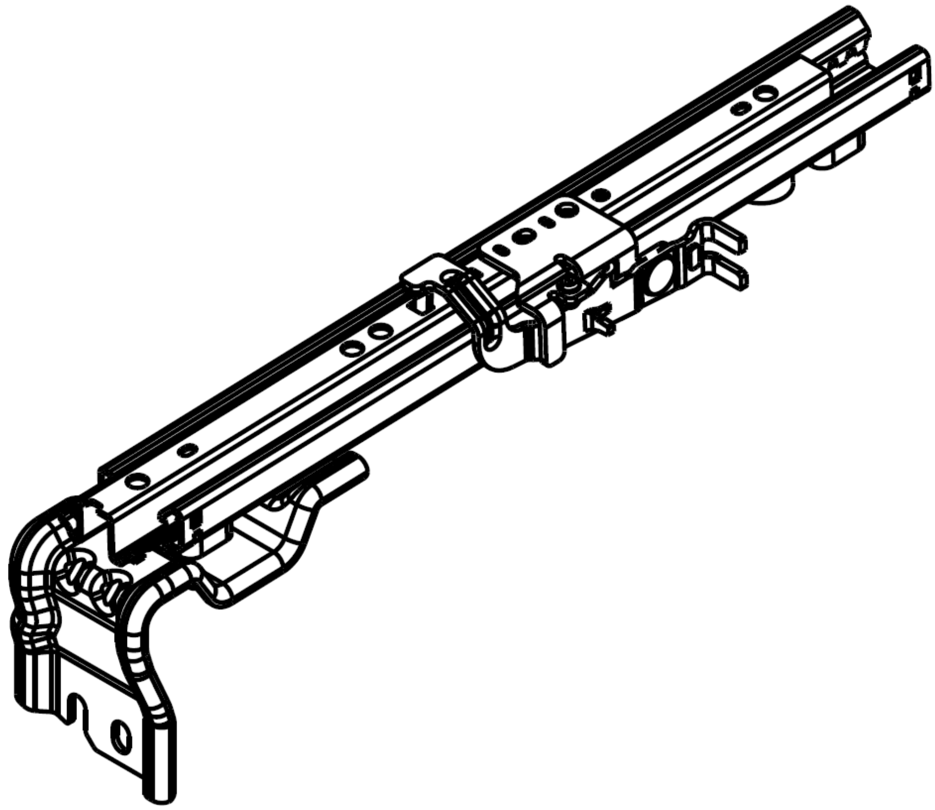

Figure 5.4: Reduced-Play Guide Drawing

The Figure 5.4 represents the new version of the guide. The difference with the previous version is the gap between the stationary rail and the slider that is reduced. Reducing play in the seat guides increases stiffness and minimizes relative motion between the guide components and directly decreases rattling and vibration noise. The preload of 7daN ensures a more stable connection particularly in driving scenarios involving small vibrations from the chassis specially when the seat has no occupant.

5.3.2 Ferrari-Origin Tube

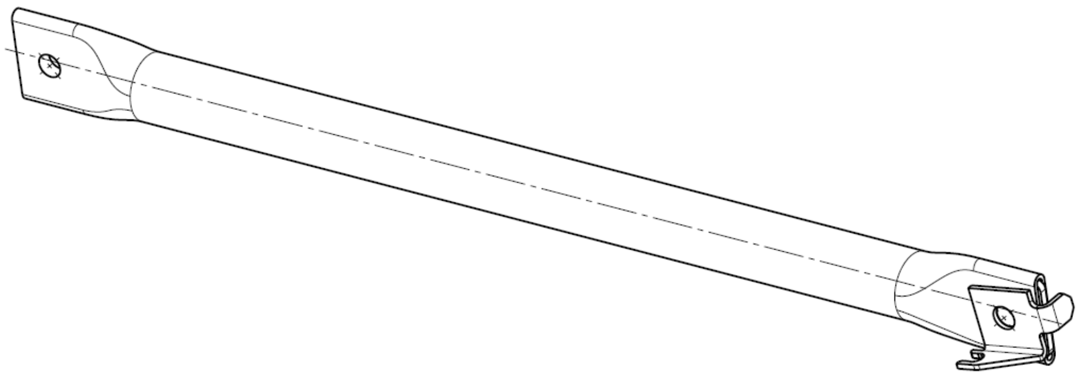

Figure 5.5: Ferrari-Origin Tube Drawing

It is introduced a new version of the tube shown in the Figure 5.5 in the rear part close to the joint, as explained in the Chapter 5.3.6. This tube is a Ferrari Origin Tube that improves stiffness and precision in the seat frame structure. The larger diameter increases the structural rigidity of the seat frame, reducing noise resonances caused by tube vibrations. Additionally, the larger contact area of the tube lowers the amplitude of oscillations. Structural stiffness ensures that the seat remains stable under dynamic loads.

5.3.3 Sub-Base with Additional Third Fixing on the Door Side

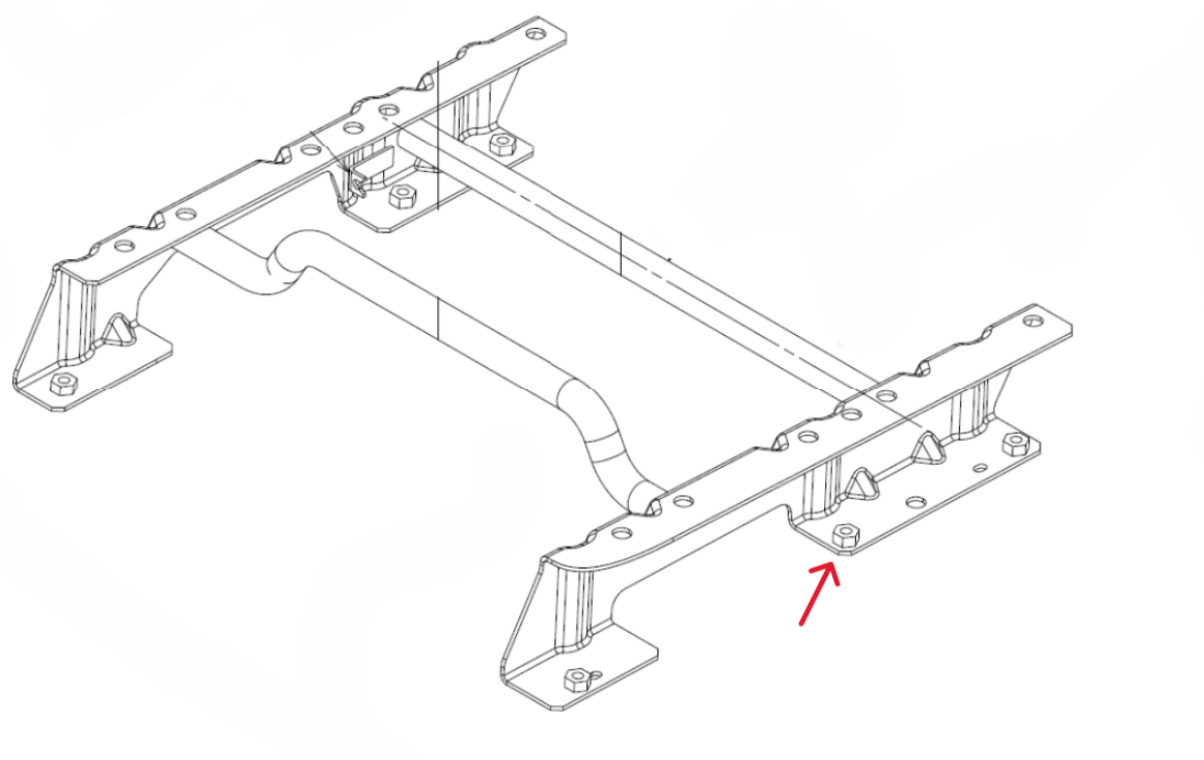

Figure 5.6: Sub-Base with Additional Third Fixing Drawing

Adding a third fixing point, as highlighted in red in Figure 5.6 , improves the distribution of forces and enhances the overall stability of the sub-base. The goal of this modification is to minimize vibrations transferred to the seat frame and reduce the possibility of noise due to flexing or oscillations phenomena. This modification should influences vibrations associated with road-induced vibrations.

5.3.4 Joint Assemblies with "Tribo-Gel" Grease

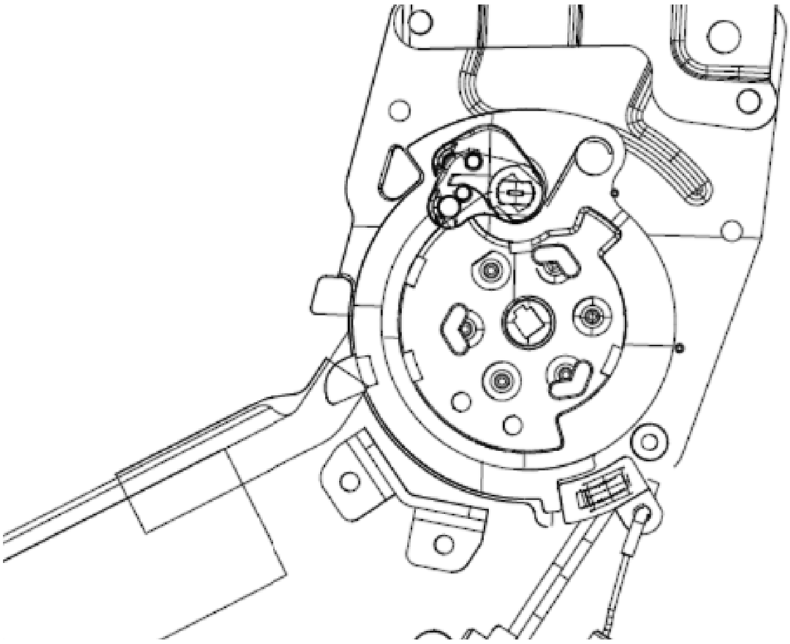

Figure 5.7: Joint Drawing

Applying "Tribo-Gel" grease in the joint that displays in Figure 5.7, reduces friction and damping at the point especially during dynamic vehicle movements. This prevents squeaks and creaks, common in areas with sliding or rotational motion. This noise phenomena typically occurs in the high-frequency range where friction-induced noises dominate.

5.3.5 Reinforced Backrest Shell

A Reinforced backrest shell should be able to prevents flexing and deformation under dynamic loads. This reduces structural noise caused by vibrations in areas with insufficient support that have a certain freedom on its micro-movements. The reinforcement shifts the natural frequencies of the backrest to higher values where structural vibrations are most likely to resonate. However, this solution was adopted just to show what the effects of a stiffer backrest shell are, without considering the implementation of this component in the production line, its cost and its design elegance. No Official Draws of this components are avaiable.

5.3.6 Non-Stressed Rear Ferrari Tube (Modified Assembly Cycle)

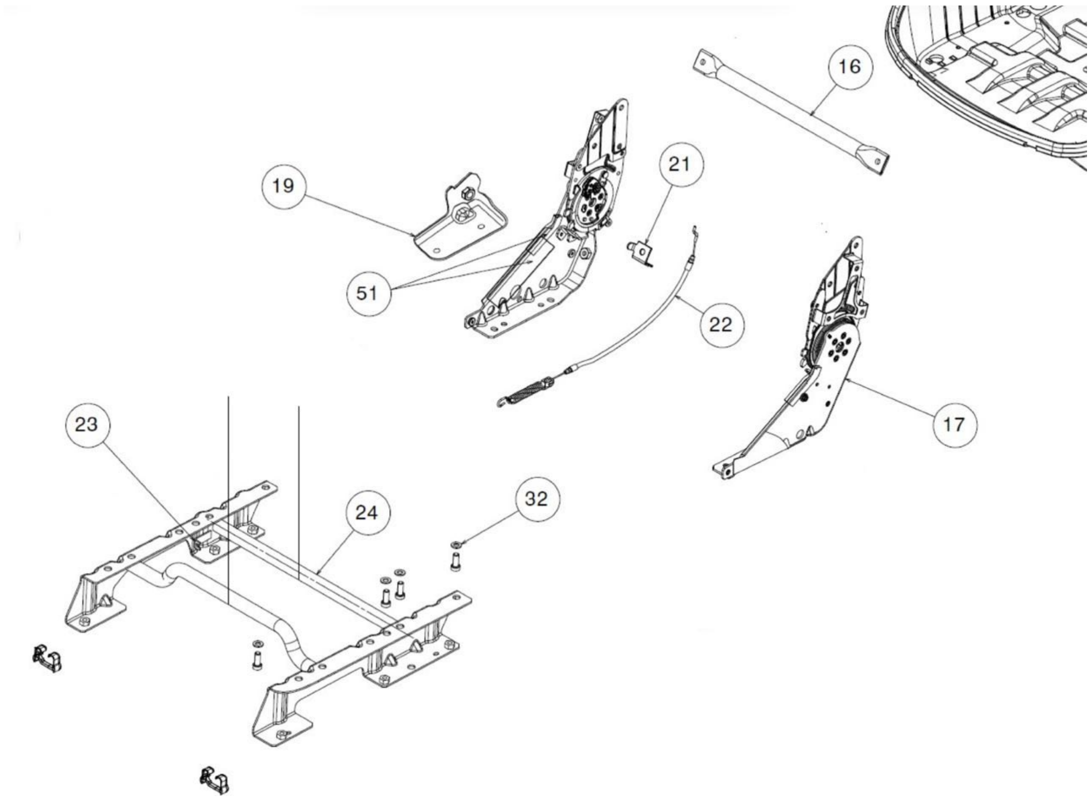

Figure 5.8: Non-Stressed Rear Ferrari Tube Assembly Drawing

The Figure 5.8 helps to understand how the Tube is not stressed during the assembly cycle. In a previous cycle, the tube was mounted and then the two joints were linked and fixed, causing a stress on the pre-fixed tube. In the new assembly cycle, both the joints and the Ferrari-Origin Tube are fixed together without causing stress in the components. Eliminating pre-stress during the assembly process ensures the tube does not store residual tension, which could lead to noise when released under dynamic conditions. A stress-free assembly also improves structural integrity. Reducing assembly-induced stress prevents vibrations that arise from residual tensions.

5.3.7 Tensioning Bar in the Backrest

A tensioning bar in the backrest is added because it increases the structural rigidity, preventing noise caused by the relative movements between the seatback and other components. It also reduces dynamic friction in the joints. However, this solution was not adopted for production due to increased complexity, cost and weight, despite its noise benefits. Official Draws of these components are not avaiable.

5.3.8 Addition of Felt Pads

		High Noise Damping
Product		51606
Backing		PET fleece
Adhesive		Rubber based
Temperature resistance		-40°C / 105°C
Thickness		800 µm
Noise damping		Class D
Abrasion resistance	5 mm	Class D
	10 mm	Class D
Adhesion to steel		5.5 N/cm
Unwind force		7.5 N/roll (30 m/min)
Hand tearability		No
Color		Black

Figure 5.9: Felt Pad Technical Schedule

In the Figure 5.9 the technical schedule and an image of the Felt Pad 51606 are shown. Felt pads are applied in areas of contact to absorb vibrations and prevent noise caused by friction between components. It also acts as dampers to dissipate vibrational energy. Felt pads are used a lot to try to reduce high-frequency noise where small contact vibrations are most pronounced.

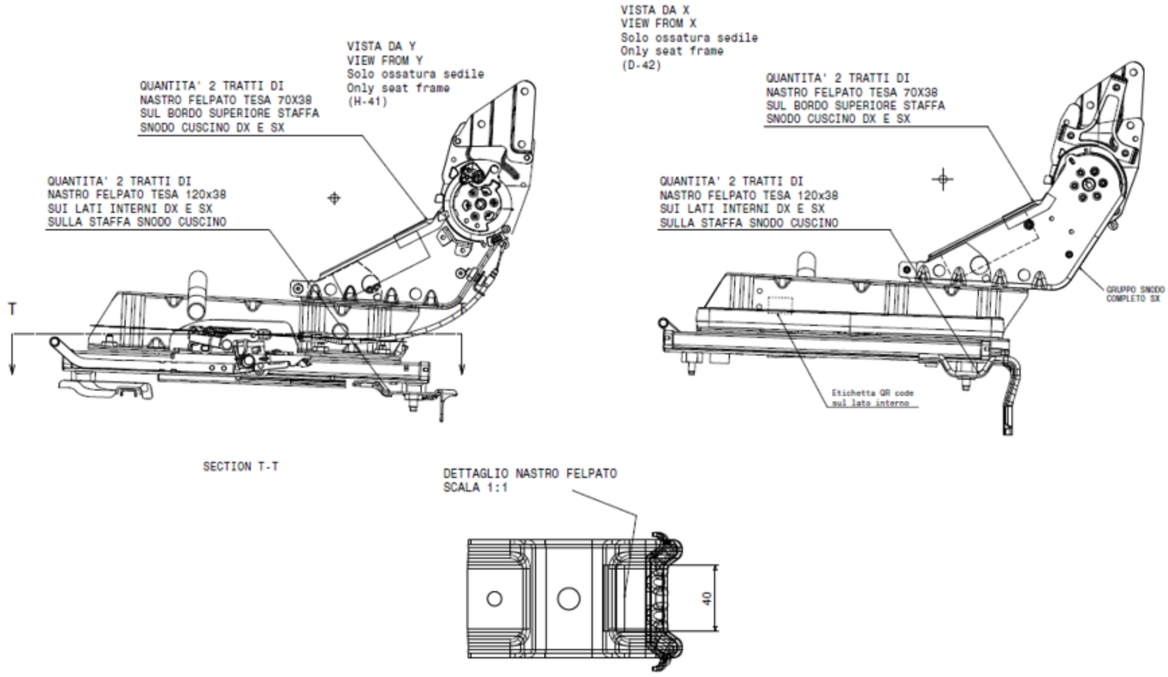

Figure 5.10: Felt Pad Application Points

The Figure 5.10 shows the point in which the Felt Pad is used:

- On the upper edge, left and right cushion joint bracket;
- On the inner sides, both left and right, on the cushion joint bracket;
- On the rail at the point indicated in the figure.

Chapter 6

Output Data

In this section it is studied the impact of multiple seat modifications on the noise behavior across a broad frequency spectrum (100 Hz to 10,000 Hz). Here, different test cases are explained considering structural reinforcements, assembly process changes, and damping solutions. By looking at the graphs, it is possible to identify the effectiveness of each intervention and understand how specific components influence noise in key frequency bands.

6.1 Noise Performance in the Scrap Seat

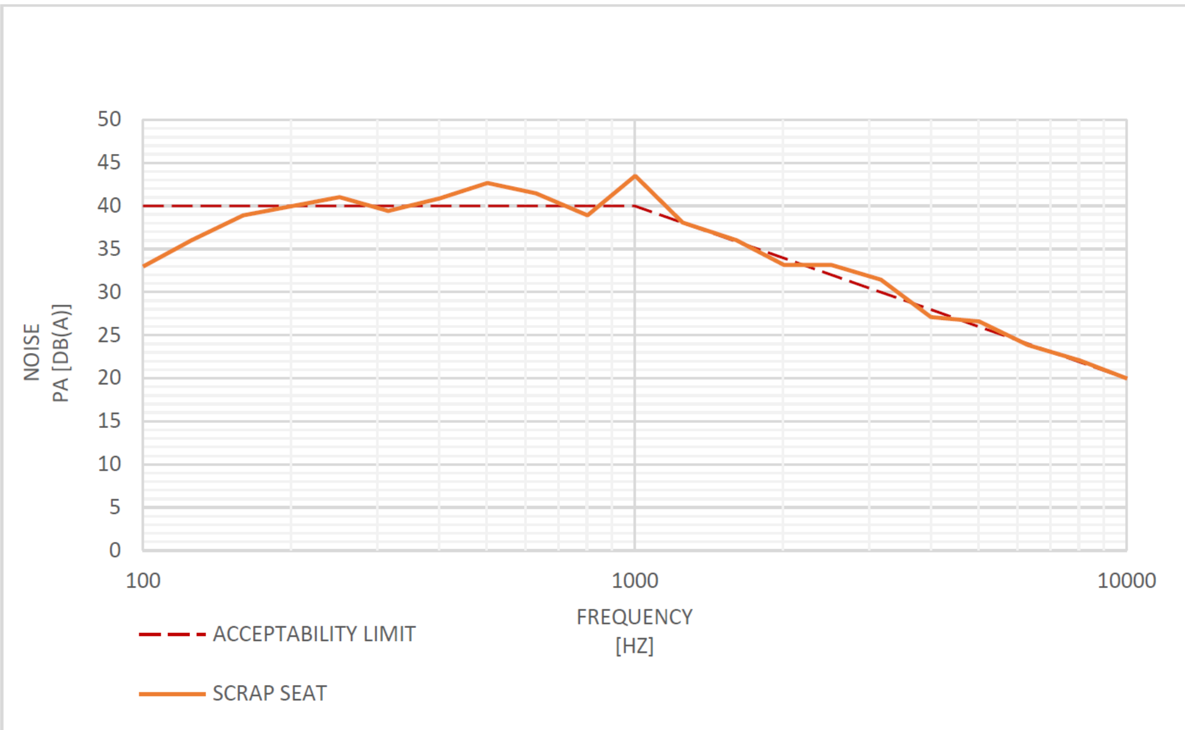

Figure 6.1: Scrap Seat Case Objective Evaluation

The **scrap seat** serves as the starting point for the upgrades discussed in this chapter. This seat, discarded by the customer (**FCA Poland**) due to excessive noise generated under dynamic conditions, represents the original production model that does not meet

the quality standards defined by the customer or by norms and outlined in paragraph 5.2. Considered the "worst-case" scenario for noise and vibration performance, the scrap seat is used as a reference in this case study to demonstrate how each modification impacts noise levels, frequency response, and overall comfort.
From a subjective point of view of the evaluation of the scrapped seat, myself and the technicians of the Sabelt laboratory have filled the SAE rating scale in function of the noises that are perceived by our ears and by the hands-on approach, and the result is shown in the figure 6.2 below.

<table>
<tr><td></td><td></td><td colspan="4">UNACCEPTABLE</td><td colspan="6">ACCEPTABLE</td></tr>
<tr><td rowspan="5">CUSTOMER VIEWPOINT</td><td>Judgment</td><td>Very poor</td><td>Poor</td><td>Less than mediocre</td><td>Mediocre</td><td>Acceptable limit</td><td>Acceptable</td><td>Discreet</td><td>Good</td><td>Very good</td><td>Excellent</td></tr>
<tr><td>Detectability</td><td>All customers</td><td colspan="3">Medium customers</td><td colspan="2">Critical customers</td><td colspan="4">Expert customers</td></tr>
<tr><td>Perceptibility</td><td colspan="3">HIGH</td><td colspan="3">MODERATE</td><td colspan="2">SMALL</td><td>VERY SMALL</td><td>NONE</td></tr>
<tr><td>Sensation</td><td colspan="2">Intolerable</td><td>Strong discomfort</td><td>Discomfort</td><td>Slight discomfort</td><td colspan="2">Small disturbance</td><td>Minimal disturbance</td><td colspan="2">No disturbance</td></tr>
<tr><td>Reaction</td><td colspan="2">Refusal</td><td colspan="2">Protest</td><td>Complaint</td><td colspan="2">Acceptance</td><td colspan="2">Appreciation</td><td>Enthusiasm</td></tr>
<tr><td>Alphanumeric scale</td><td>Voting Scale (1-10)</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td><td>6</td><td>7</td><td>8</td><td>9</td><td>10</td></tr>
<tr><td colspan="2">Corrective Actions</td><td colspan="2">Radical and immediate intervention</td><td colspan="3">Timely corrective intervention</td><td>To be improved</td><td colspan="2">Requires attention</td><td colspan="2">OK</td></tr>
</table>

Figure 6.2: Scrap Seat Case Subjective Evaluation

As can be seen, a low score in 'Judgment', 'Perceptibility', 'Sensation', and 'Reaction' leads to a low overall Rating Scale, making this seat one that requires attention.
In fact, the scrap seat may exhibit **excessive play** in specific components, such as the guides or joints, resulting in **rattling** or **slapping noises** during use. These noises are typically caused by parts moving or vibrating against one another without sufficient damping or isolation. Additionally, **excessive friction** or **rubbing** between components can occur when parts come into contact without proper lubrication or damping materials, generating unwanted frictional noises. Structural resonances at certain frequencies are another common issue with the scrap seat. These resonances can cause vibrations that are transferred from the vehicle chassis or road inputs to the seat, amplifying specific frequencies and producing **buzzing** or **humming** noises. Through the modifications applied in **Cases 1–4**, an attempt is made to eliminate or at least reduce these issues, and the improvements or worsenings achieved are described in detail in the following sections.

6.2 Case 1 Analysis (Yellow Curve)

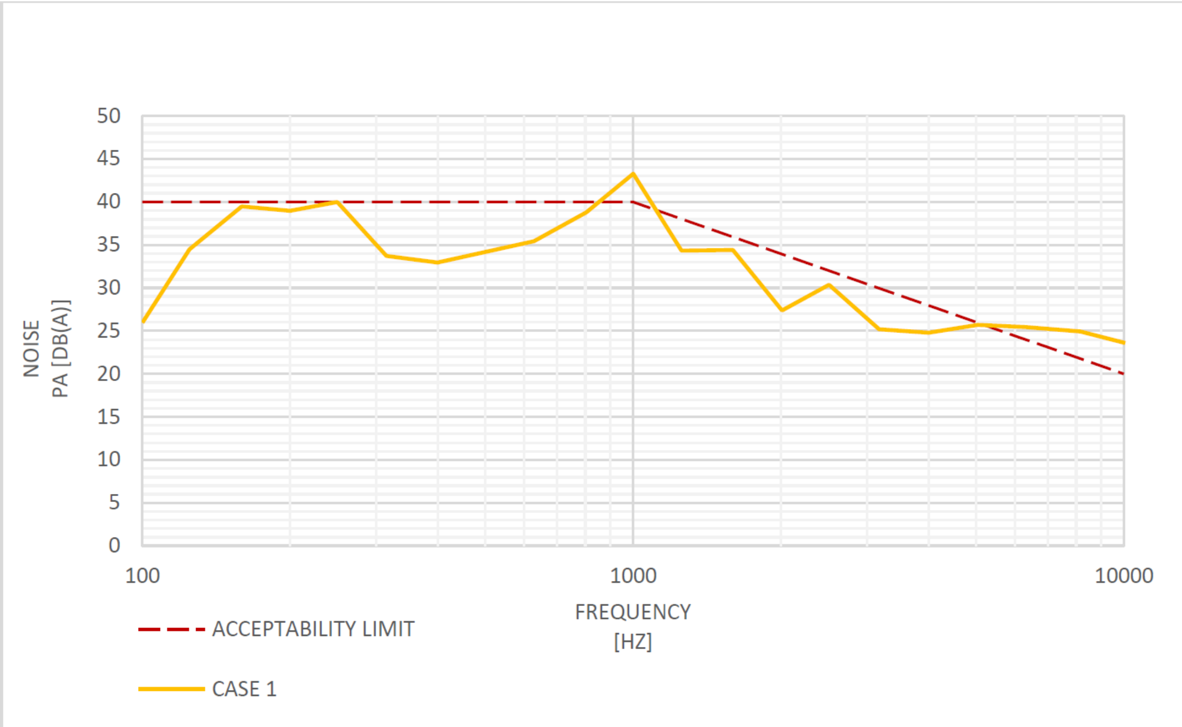

Figure 6.3: Case 1 Objective Evaluation

This case incorporates five modifications aimed at improving the seat's noise across various frequency ranges. The modifications are:

- Reduced play Guides with 7 daN preload;
- Ferrari-origin tube (larger diameter);
- Sub-base with additional third mounting on the door side;
- Hinges lubrificated with Tribo-Gel grease;
- Backrest shell reinforced.

The yellow curve in the graph demonstrates significant improvements compared to the baseline (scrap seat). At **Low Frequencies (100–800 Hz)**, there is a noticeable reduction in noise, attributed to several key modifications like the reduced guide play, the use of a larger diameter tube to mitigate noise peaks from structural vibrations, and the addition of a third fixing point on the seat base. Without sufficient preload, the seat guides can shift or rattle in response to small vibrations from the vehicle body or road surface; this problem is particularly evident when the seat is unoccupied. The absence of an additional fixing point can lead to excessive flexing or vibrations of the seat structure, especially during dynamic vehicle movements such as cornering or traversing rough surfaces. These modifications are able to solve these issues, ensuring all components remain tightly fixed. At **Mid Frequencies (800–2,000 Hz)**, the improvements are less consistent. Around 1,000 Hz, a resonance of certain components causes noise amplification, suggesting the need for further investigation and refinement in this range. For **High Frequencies (2,000–5,000 Hz)**, the application of Tribo-Gel grease effectively suppresses squeaking noises, maintaining compliance with noise acceptability limits. However, the increased rigidity introduced by some modifications occasionally shifts certain resonances into very-high frequency range, presenting an area for potential future optimization. Overall, the results confirm that **Case 1** provides a solid foundation for achieving significant NVH improvements,and it could be considered as the starting point of the optimization process that will be achieved in the final case study seat.

6.3 Case 2 Analysis (Green Curve)

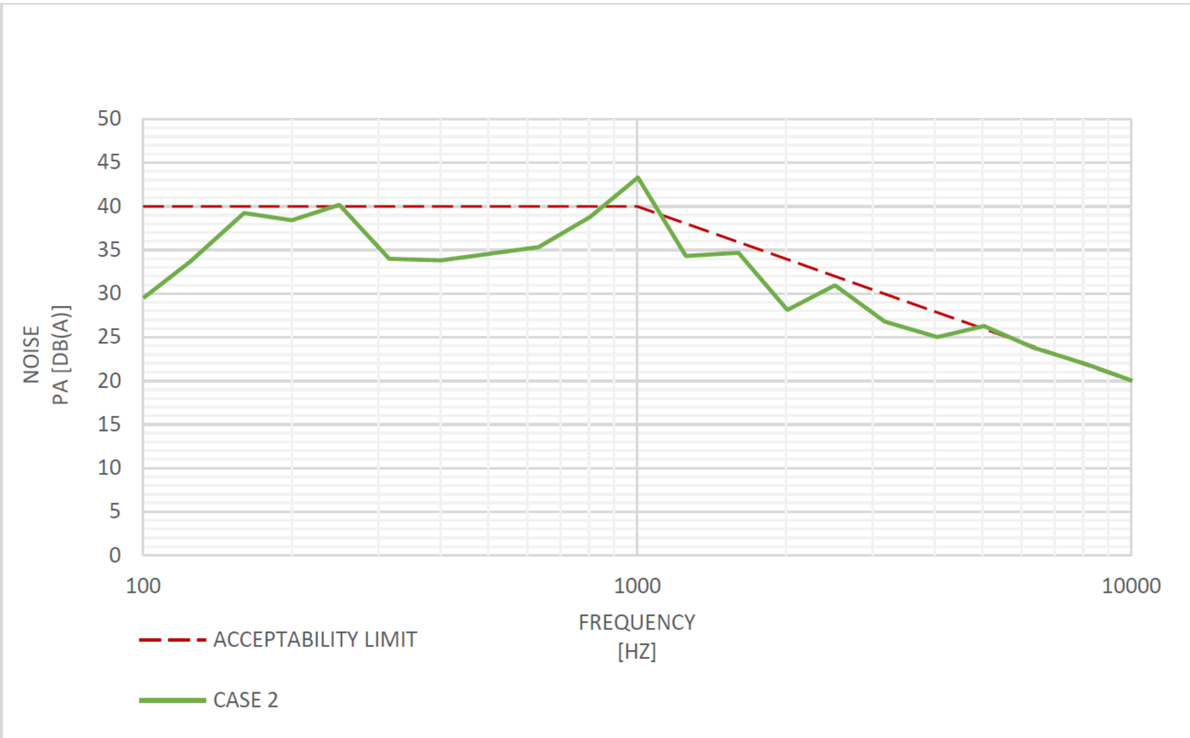

Figure 6.4: Case 2 Objective Evaluation

In Case 2, the following modifications were implemented:

- Guides with Reduced Play and 7 daN of pre-Load;
- Unstressed Rear Ferrari Tube (Non-Tensioned Tube);
- Lubricated Joints with Tribo-Gel;
- Tension Bar in the Seatback.

At **Low Frequencies**, the green curve shows a slight noise reduction compared to the yellow curve. This improvement can be attributed to the removal of stresses in the rear tube, which mitigates structural noises phenomena. The addition of the tension bar further stabilizes the seat structure, enhancing overall performance even if the trade-off between performance-cost.implementation in line production is not positive. At **Mid Frequencies (600–2,000 Hz)**, the reduction of play in the guides and the application of Tribo-Gel grease to the joints effectively minimize vibrations caused by relative mechanical movements, showing a clear improvement compared to the scrap seat, while, if compared with case 1, due to the fact that these two modifications are the same in both cases, no improvements are noticed. The tension bar also helps limit friction or nonlinear movements, resulting in noise reductions in the 500–1,500 Hz range that are comparable to the improvements seen in Case 1. At **High Frequencies (2,000–5,000 Hz)**, the performance of Case 2 does not exhibit significant improvements over Case 1. However, at **Very High Frequencies (5,000–10,000 Hz)**, the Tribo-Gel grease appears to partially dampen high-pitched noises generated by joint friction. Additionally, the absence of the reinforced backrest shell seen in Case 1 reduces the structural rigidity, contributing to a reduction in noise levels in this range. Compared to the scrap seat, Case 2 demonstrates a significant reduction in noise across certain frequency ranges, confirming the effectiveness of some of the implemented modifications. The use of the tension bar and an improved assembly process greatly enhances the seat's structural integrity. Case 2 highlights the importance of optimizing the seat assembly process and that the tension bar stabilizes the backrest and prevents high-frequency resonances. Overall, Case 2 represents a partial improvement over Case 1, particularly at very high frequencies, demonstrating that these frequency range noises can be optimized.

6.4 Case 3 Analysis (Blue Curve)

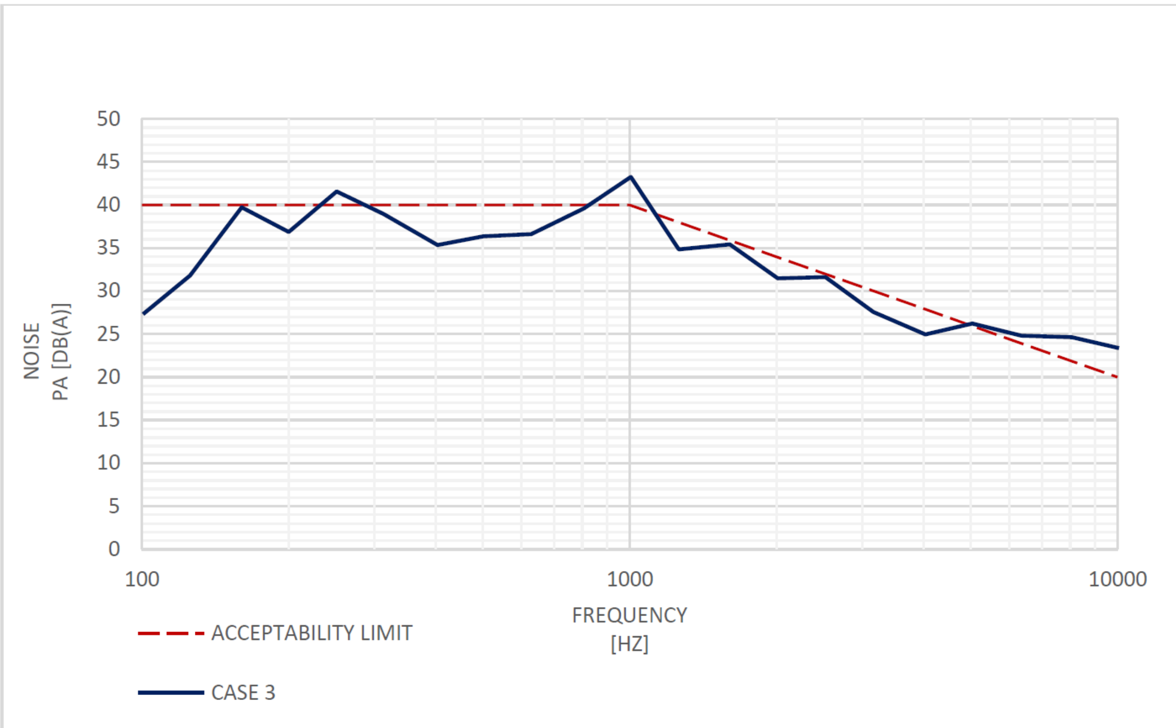

Figure 6.5: Case 3 Objective Evaluation

The configuration of the Case 3 is built upon the enhancements introduced in Case 2 but excludes the tension bar in the backrest. This omission allows for a focused evaluation of other modifications, such as the non-forced rear tube and the Tribo-Gel grease applied to the hinges, while assessing the seat's behavior without the backrest reinforcement.
In the **Low Frequency** range (100–700 Hz), this case demonstrates clear improvements over the scrap seat, with performance comparable to Case 2. In fact, the noise reduction in this range is largely due to the non-forced rear tube, which mitigates vibrations caused by road inputs, and the guides with preload, which enhance stability by reducing play. As this range is particularly sensitive to vibrations transmitted from the chassis, these modifications effectively reduce it, resulting in lower noise levels.
In the **Mid Frequency** range (700–1,500 Hz), Case 3 performs similarly to Case 2, showing significant improvement over the scrap seat but slightly higher noise levels than Case 2. This range is particularly affected by structural vibrations, such as those in the backrest, and hinge-related friction noise. The Tribo-Gel grease is helpful to reduces noise from the hinges and the lack of backrest stabilization results in higher amplitude peaks between 800–1,500 Hz, as the backrest is more prone to resonant behavior without the tension bar. At **High Frequencies** (2,000–5,000 Hz), Case 3 shows a significant reduction in noise compared to the scrap seat and this improvement is primarily due to the effective application of Tribo-Gel grease, which minimizes squeaking and friction-related noise at the hinges. However, the absence of the tension bar results in less pronounced noise reduction compared to Case 2, where the backrest stabilization offered additional benefits in this range. At **Ultra-High Frequencies** (5,000–10,000 Hz), Case 3 maintains a reduction in noise compared to the scrap seat, performing similarly to Case 1 in this range. The Tribo-Gel grease contributes to the dampening of hinge-related friction noise, though the lack of backrest reinforcement does not significantly affect performance at these frequencies. Compared to the scrap seat, Case 3 demonstrates a substantial reduction in noise across all frequency ranges, with particularly noticeable improvements in the low and mid-frequency ranges. The Tribo-Gel grease effectively reduces hinge-related friction noise, while the reduced play in the guides enhances the seat's stability. However, the absence of the tension bar limits Case 3's effectiveness at mid-to-high frequencies, where additional backrest stabilization could have further reduced noise. Despite this limitation, Case 3 remains a viable solution with considerable improvements in noise performance compared to the scrap seat. It highlights the importance of found a evaluable solution to reduce the very-high frequency noise that could sensibly affect the hearing.

6.5 Case 4 Analysis (Sky Blue Curve)

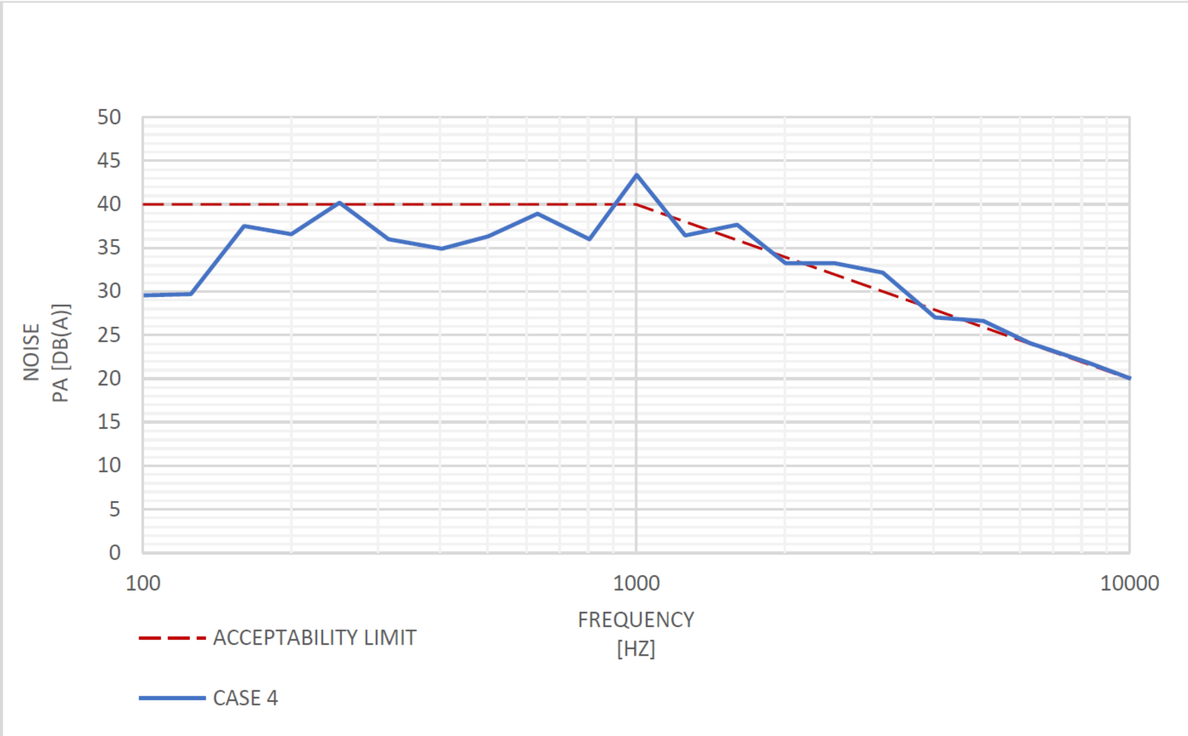

Figure 6.6: Case 4 Objective Evaluation

Case 4 represents the most extensive modification, incorporating all the changes introduced in Case 1, Case 2, and Case 3, with also the addition of the felt pads. This case aims to assess the full impact of these combined modifications on the seat's noise and vibration performance across a wide frequency spectrum, providing a holistic improvement in NVH characteristics. Before of going into the details of this case study, it is important to underline that this solution cannot be implemented due to its high cost and time required in the production line. However, it is an interesting study, helping in the choose of the final modifications. At **Low Frequencies (100–500 Hz)**, Case 4 demonstrates significant enhancements. Vibrations originating from road inputs or vehicle body movements, which are major contributors to noise in this range, are effectively mitigated, due to the reduced play guides and Ferrari-style rear tube that works together to dampen low-frequency vibrations, while the felt pads, although primarily designed for high frequencies, also contribute by damping certain mechanical interactions. As a result, Case 4 achieves the lowest noise levels in the low-frequency range among all cases, greatly improving occupant comfort by isolating them from harsh vibrations. In the **Mid-Frequency Range (500–1,500 Hz)**, felt pads play an important role in reducing noise caused by mechanical interactions and friction within the seat assembly. While the Ferrari-style tube provides minor benefits in reducing structural resonances, the primary improvements comes from the elimination of friction-induced noise and mechanical rattles. These modifications ensure that mid-frequency vibrations, which often feel sharp or harsh, are significantly smoothed. This leads to a better acoustic and vibrational experience, enhancing overall comfort. In the **High-Frequency Range (1,500–5,000 Hz)**, the combination of all the modifications does not work properly, in fact, the noise level is higher even if it is compared to the scrap seat. this is probably due to the amplification of the resonance phenomena caused by the structural changes. At **Ultra-High Frequencies (5,000–10,000 Hz)**, Case 4 perform exceptionally well. The felt pads are highly effective in attenuating unwanted sounds, such as squeaks and high-pitched resonances. This results in a seat that not only minimizes acoustic disturbances but also provides a quieter and more refined feel during operation. This case shows substantial improvements across all frequency ranges when compared to the scrap seat. The low-frequency range benefit comes significantly from the combined effects of the reduced play guides and Ferrari-origin tube, which is very good at isolating vibrations. The mid-frequency range sees improvements due to the removal of friction-induced noises and the damping effects of the felt pads, while the high and ultra-high frequencies are notably quieter thanks to the pads' ability to suppress resonances and squeaks. In conclusion, it is created a seat that is quieter, more stable, and more comfortable across the greatest part of the frequency spectrum, with the exception of the high frequency range.

Chapter 7

Overall Analysis

This chapter focus into the modifications implemented during the different tests seat through all the cases to enhance the performance of the car seat, with a focus on their effectiveness in mitigating noise and vibration issues across the frequency range that goes from 100 Hz to 10000 Hz. The solutions applied are outlined, detailing the specific contributions of individual components in addressing distinct noise challenges. Additionally, the rationale behind modifications that were ultimately excluded from the final design is examined, offering insights into the decision-making process and the pursuit of an optimal balance between performance, practicality, and cost-effectiveness.

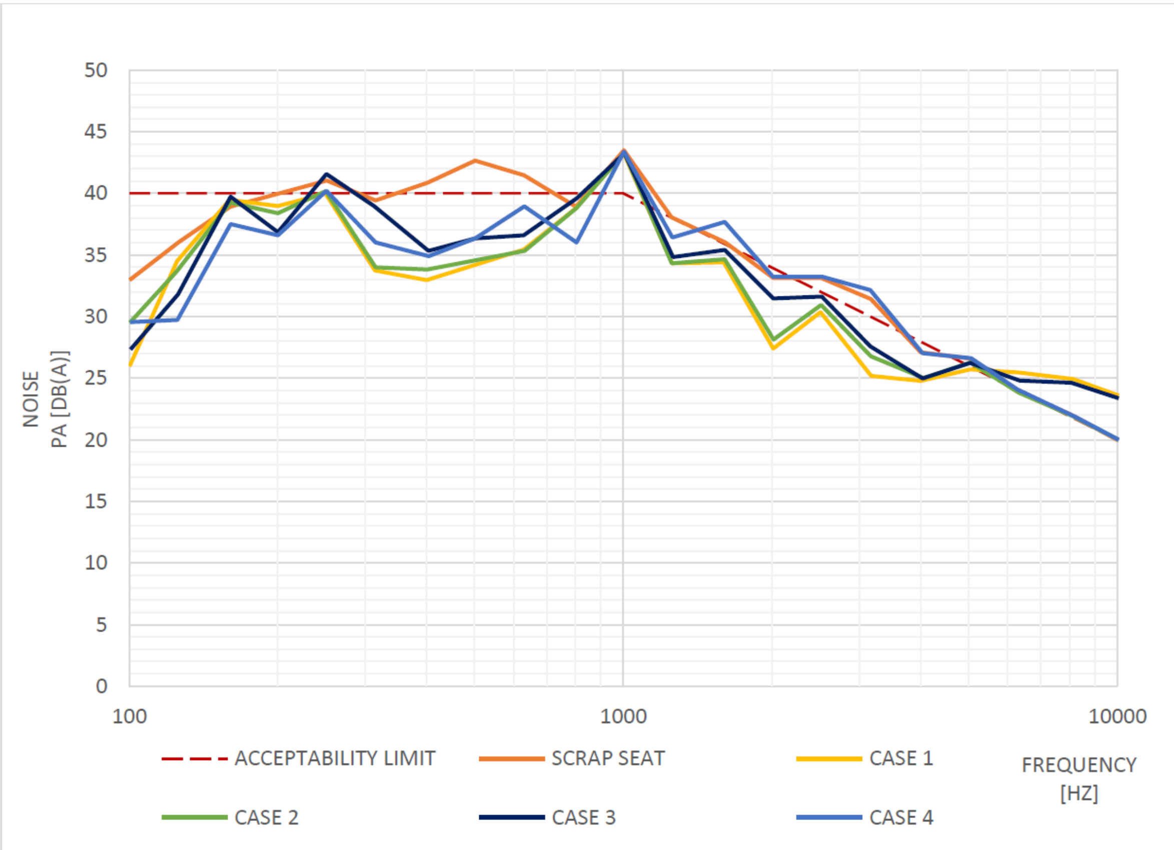

Figure 7.1: Seat Optimization Cases Objective Evaluations

The Figure 7.1 helps to practically see what the key differences between all the Cases are studied up to know, allowing a technical comparison in the paragraphs below. The chapter concludes with a detailed analysis of the final configuration, supported by graphical data, showcasing its ability to meet the required standards while balancing industrial feasibility.

7.1 Comprehensive Analysis Across All Cases

7.1.1 Effect of Assembly Process and Stress Relaxation

Comparing the configurations across all cases, it is possible to notice that **Case 2** (green curve) introduces a significant enhancement by optimizing the assembly process through the implementation of the "unstressed" rear tube, minimizing the residual stress that was retained in the rear tube in the **Case 1**. This stress relaxation helps to reduce undesirable resonance peaks, resulting in smoother vibro-acoustic performance across the entire frequency range. Additionally, the reduced residual stress improves the material's durability by mitigating the risk of fatigue and microcracking, enhancing the seat's overall reliability.

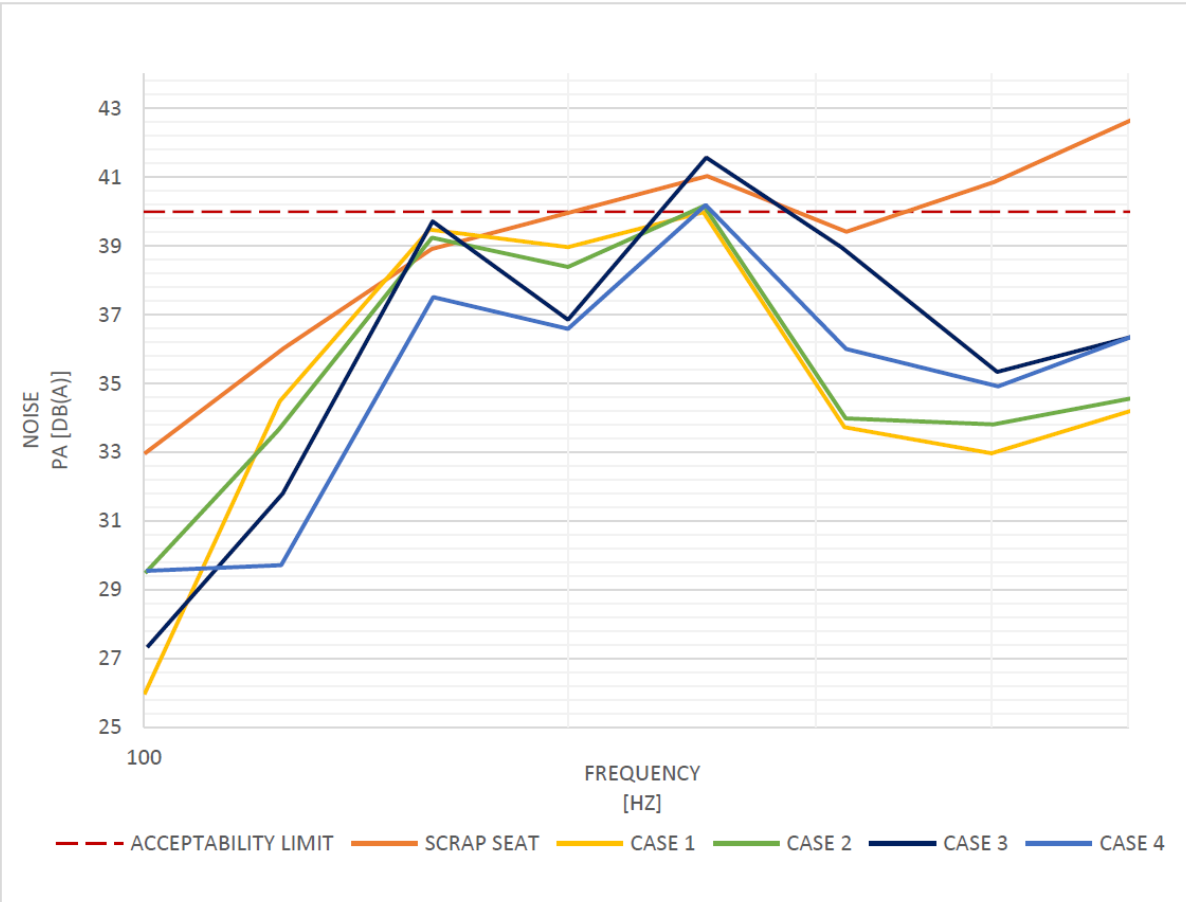

Figure 7.2: Effect of the Assembly Process Optimization

- **Frequency Range Affected:** Low frequencies (below 500 Hz).
- **Impact:** Stabilized structural resonance and minimized low-frequency noise events.

Case 3 (blue curve) and **Case 4** (sky blue curve) maintain the benefits of the unstressed rear tube, as in the Case 1 and Case 2. These configurations continued to minimize residual stress, contributing to smoother and more stable dynamic behavior. Among the two, **Case 4** demonstrated the most substantial improvements at **low frequencies**, attributed to the addition of felt pads and reinforced components. The felt pads are damping mechanical interactions and reducing resonance, while the reinforced components added stability to the structure, effectively isolating vibrations and minimizing noise. This combination made Case 4 the best configuration in terms of noise af low frequency.

7.1.2 Tension Bar and Tribo-Gel Joints

In **Case 2**, the inclusion of the tension bar in the backrest work with the Tribo-Gel-treated joints to enhance the stiffness of the seatback while effectively reducing friction-induced noise, particularly in the mid-to-high-frequency ranges. This combination provided greater structural stability, but it does not helps to minimize micromovements and suppressing mechanical noise amplification. In **Case 1**, the absence of the tension bar in the seatback is partially covered by the reinforced backrest shell that enhances the stiffness of the seatback. In **Case 1**, the presence of the third mounting on the sub-base allows lower flexibility, reducing micromovements that lower mechanical noise, particularly in the mid-frequency range near 1,000 Hz. This better stabilization highlight the necessity to incorporate the additional fixing. In **Case 3** and **Case 4**, the tension bar is omitted, leading to slightly reduced performance in the mid-to-high-frequency ranges compared to Case 2. The absence of this structural reinforcement left the backrest more prone to resonant behavior, while additional stabilization could have improvements reducing noise levels. Nonetheless, the application of Tribo-Gel in these cases continued to provide significant friction reduction. The tension bar solution was ultimately excluded from the final design, because it is not aligned with the design standards required for the project.

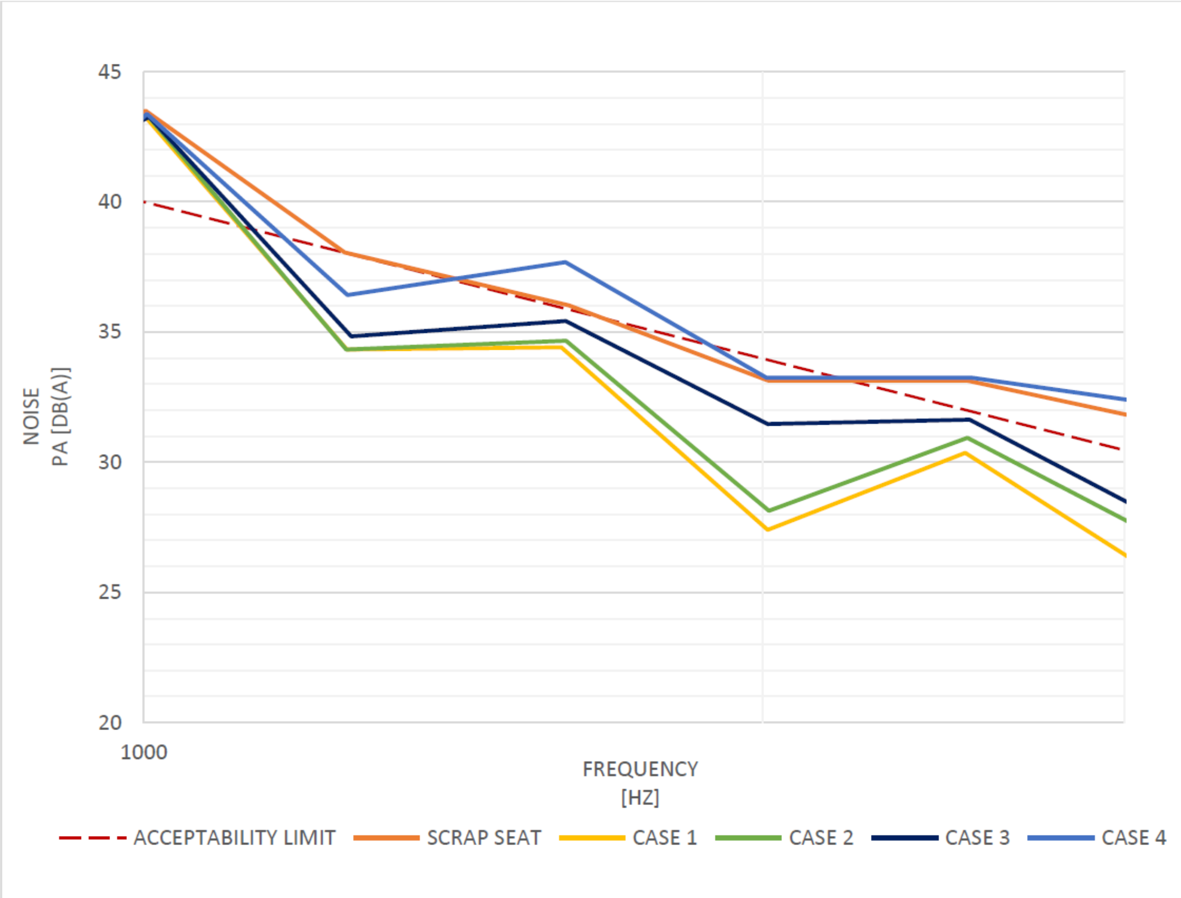

Figure 7.3: Influence of Tension Bar and Tribo-Gel Joints

- **Frequency Range Affected:** Mid frequencies (1,000 Hz to 3,000 Hz).
- **Impact:** Reduced friction-induced squeaks and improved acoustic performance.

7.1.3 Guide Rails with Reduced Play

The introduction of guide rails with reduced play effectively improve one of the primary sources of mechanical noise coming from micromovements and friction. In earlier configurations, loose tolerances in the guide rails allow minor movements, which translated into audible vibrations, particularly prominent in the mid-frequency range. These noise events are significantly reduced, resulting in a more stable and controlled seat movement. This modification not only minimized mechanical noise but also contributed to a more refined and consistent acoustic profile. Due to its substantial positive impact on the seat's overall noise performance, this enhancement was implemented across all cases.

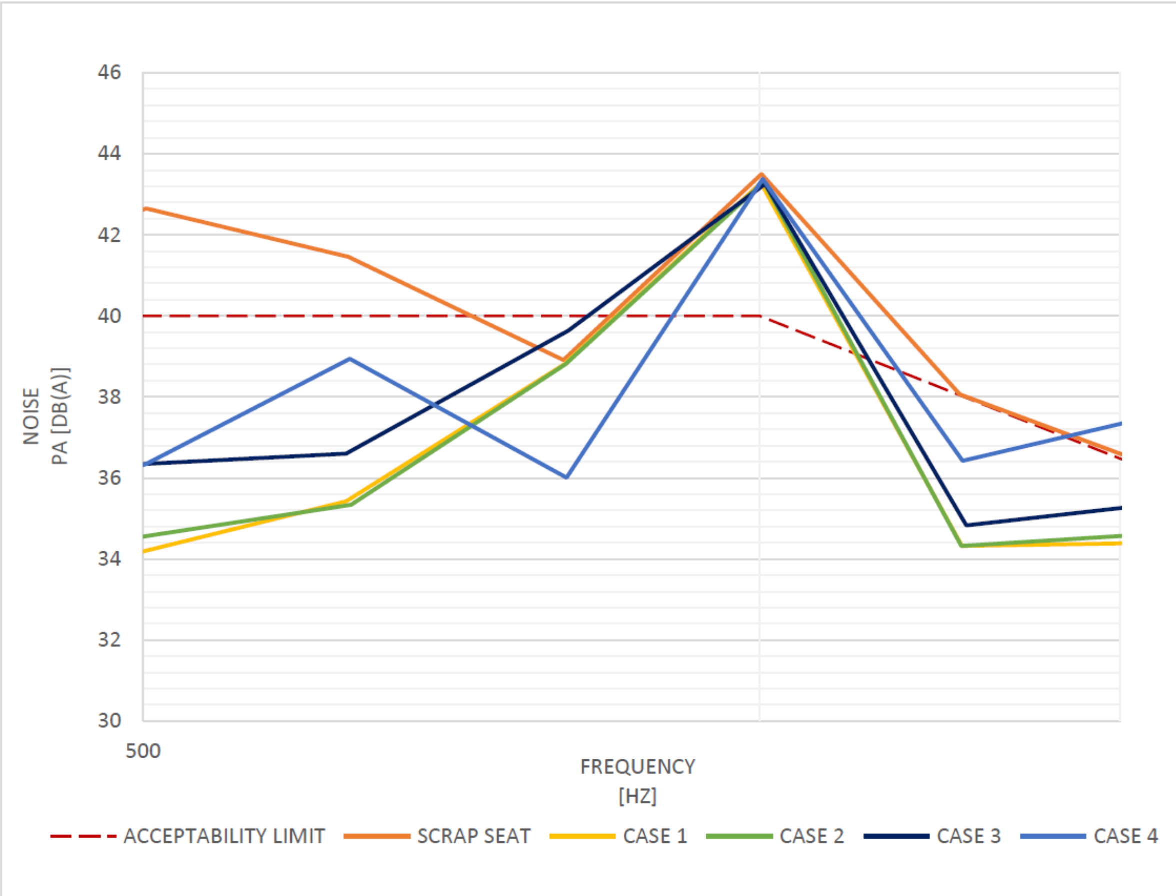

Figure 7.4: Effect of the Guide Rails

- **Frequency Range Affected:** Mid frequencies (500 Hz to 1,500 Hz).
- **Impact:** Reduced mechanical noise caused by friction and micromovements, improving the overall acoustic experience and enhancing perceived seat quality.

7.1.4 Third Fixing Point on the Under Base

The addition of a third fixing point on the seat's under base significantly improved structural rigidity, creating a more stable attachment to the vehicle body. This enhancement reduce resonance in the low-to-mid frequency range, where structural vibrations were previously more pronounced. This modification was implemented only in **Case 1** but was later incorporated into the final configuration due to its benefits. Its combination of high impact on noise reduction and low implementation cost and time made it an essential modification for optimizing the seat's noise response.

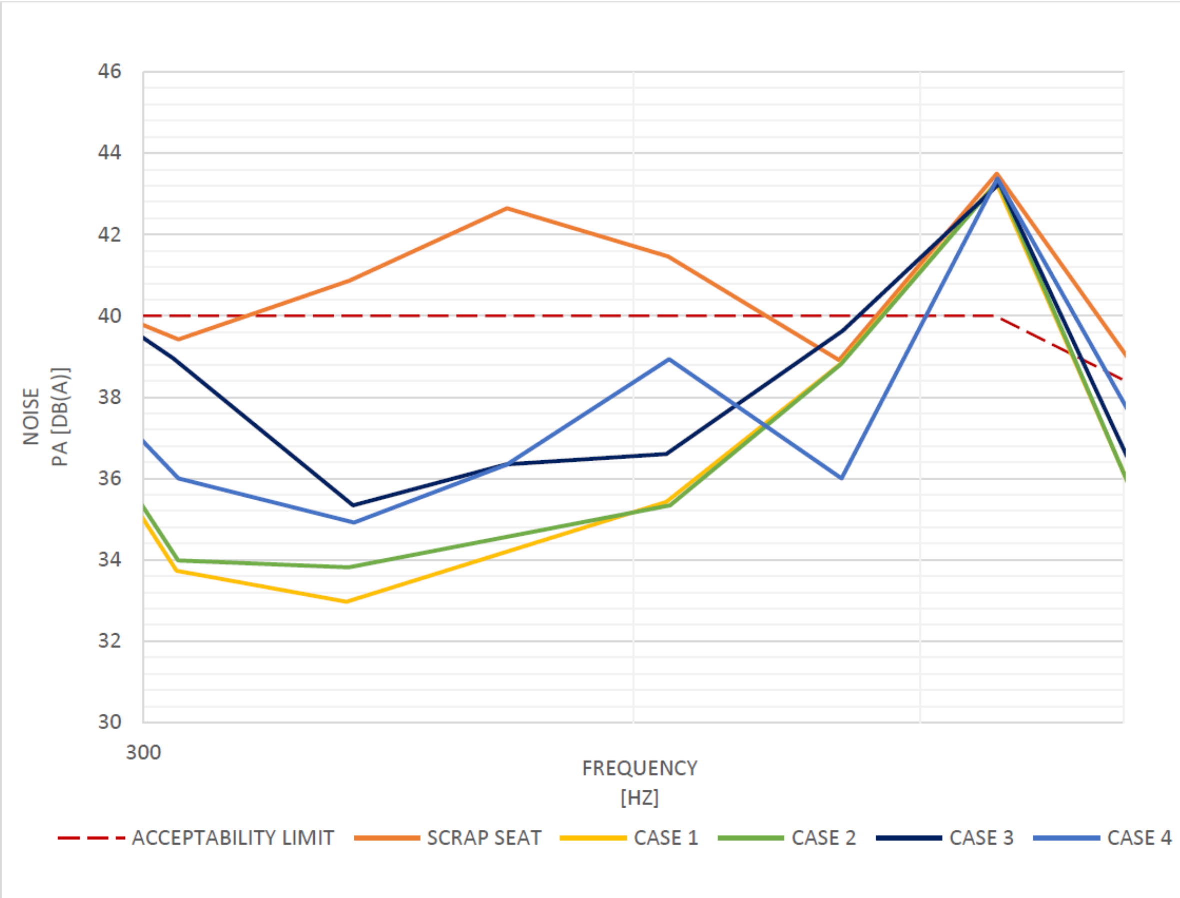

Figure 7.5: Influence of the Third Fixing Point on the Under Base

- **Frequency Range Affected:** Low-to-mid frequencies (300 Hz to 1,200 Hz).
- **Impact:** Enhanced structural integrity and reduced vibrations.

7.1.5 Felt Tape

The application of felt tape specifically mitigate high-frequency noise issues, reducing high-pitched squeaks caused by surface-to-surface contact between components. Acting as an effective dampening layer, the felt tape reduces frictions. This simple yet highly effective solution significantly improved the acoustic profile in the high-frequency range. Although felt tape was used only in **Case 4**, it was directly incorporated into the final configuration due to its substantial benefits. Its ability to achieve significant high-frequency noise reduction, combined with its very low-cost implementation, made it a modification that will be implemented on the final configuration.

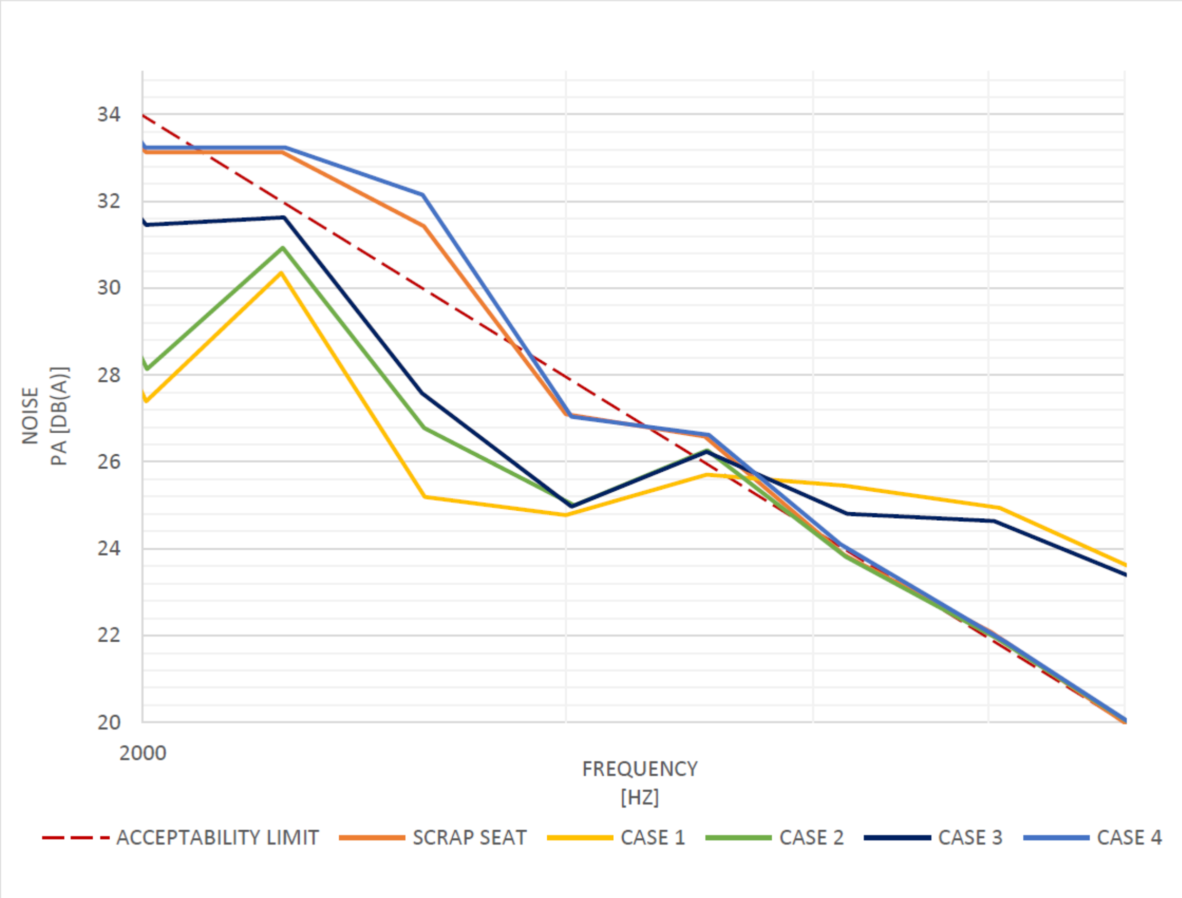

Figure 7.6: Effect of the Felt Tape

- **Frequency Range Affected:** High frequencies (above 2,000 Hz).
- **Impact:** Successfully mitigated high-frequency squeaks, contributing to a quieter and more refined seat system.

7.1.6 Conclusions

Across all cases, improvements were observed compared to the baseline scrap seat (orange curve). Among the configurations, **Case 2** emerged as the most balanced solution, offering enhancements in acoustic performance, structural integrity, and manufacturing consistency. Key modifications in Case 2, including the unstressed rear tube, Tribo-Gel lubrication, and tension bar, effectively addressed major sources of noise and vibration, particularly in the low and mid-frequency ranges. While **Case 3** and **Case 4** omitted the tension bar due to production constraints, both configurations still achieved significant improvements, especially in reducing high-frequency noise. However, the absence of the tension bar slightly compromised performance in the mid-to-high-frequency ranges, emphasizing the role of structural stabilization in these frequency bands. **Case 3** and **Case 4** remain viable alternatives, with Case 4 delivering the best performance in very low and very high frequency ranges, thanks to the inclusion of felt pads and more extensive modifications. The final results, as detailed in paragraph 7.2, underscore the critical balance between technical performance and industrial feasibility in automotive seat design.

7.2 Final Configuration

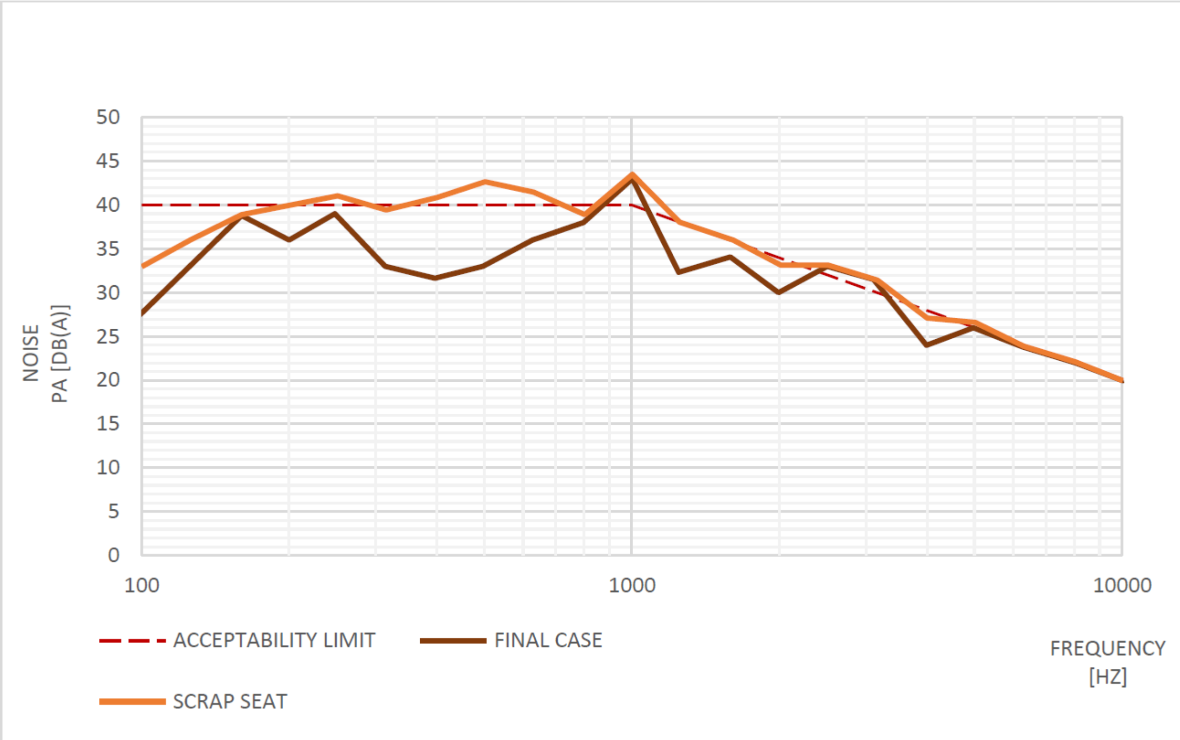

Figure 7.7: Final Case Objective Evaluation

The final configuration implemented in the seat design included the following modifications:

- Guide Rails with Reduced Play;
- Ferrari-Origin Tube;
- Third Fixing Point on the Under Base;
- Tribo-Gel Grease for the Joints;
- Non-forced Rear Ferrari Tube;
- Felt Tape.

These modifications were carefully selected for their ability to enhance the NVH performance of the seat while ensuring feasibility in terms of production costs, assembly time, and overall weight. One important decision was the exclusion of the **tension bar** in the seatback, despite its demonstrated benefits in reducing noise and vibration, as seen in Case 2. This exclusion was driven primarily by the increasing of the **production costs**, **assembly complexity**, and **additional weight**. Aesthetic considerations also played a role, as the tension bar's appearance could not be in line within the vehicle cockpit. Key modifications included the **Ferrari-origin tube** and the **non-forced assembly process** for the rear tube, which effectively managed structural resonances and minimized low-frequency vibrations. The **guide rails with**

reduced play, combined with the **application of Tribo-Gel grease**, successfully addressed mid-frequency mechanical noise caused by friction and micromovements. For high-frequency issues, the felt tape proved highly effective in eliminating squeaks and rattles, contributing to a quieter and more comfortable user experience. Overall, the selected modifications present a **practical and efficient solution** to the NVH challenges of the original seat design. Looking ahead, if future developments allow for adjustments to cost, weight, or production time, reconsidering the inclusion of the tension bar could provide further optimization, particularly for mitigating noise and vibration in the mid-to-high frequency ranges. This configuration underscores the importance of balancing technical performance with industrial feasibility in automotive design, illustrating how it is important deliver high-quality results within real-world constraints.

Chapter 8

Conclusions

This chapter offers a reflection on the balance achieved between technical excellence, regulatory compliance, and cost-effectiveness in the final design.

8.1 Work Recap

This case study focused on optimizing the vibrational response of an automotive seat system, starting from an unacceptable condition that caused discomfort within the vehicle cockpit. The primary goal was to identify noise sources exceeding defined thresholds across various frequency ranges and to understand their root causes. Active participation in simulating different road condition excitations applied to the seat through the shaker, combined with a hands-on approach to physically feel the system's vibrations, was the phase that helps in identifying primary noise sources. The methodology adopted for this study integrated advanced simulations, iterative prototyping, and experimental testing to improve noise response within specific frequency ranges. Once the noise sources were identified, an iterative testing procedure enabled tangible evaluation of design changes. This approach allowed the Sabelt team to assess the impact of each configuration and select the optimal combination of modifications to enhance the seat's vibrational response while adhering to stringent industry regulations for mass production. The combination between theoretical analysis and hands-on experimentation proved to be an effective strategy, providing a comprehensive understanding of the testing procedure that could be applied to other vehicle components. The final design achieves a balance between noise reduction, aesthetic appeal, and compliance with industry standards. This enables the customer to offer vehicles equipped with higher-quality seats without significantly increasing the final cost.

8.2 Final Evaluations

The final design achieved noise levels consistently below the acceptability threshold. Specially if it is compared with the initial configuration, significant advancement is clearly obtained, and the seat is able to pass both the subjective and objective regulation standards.

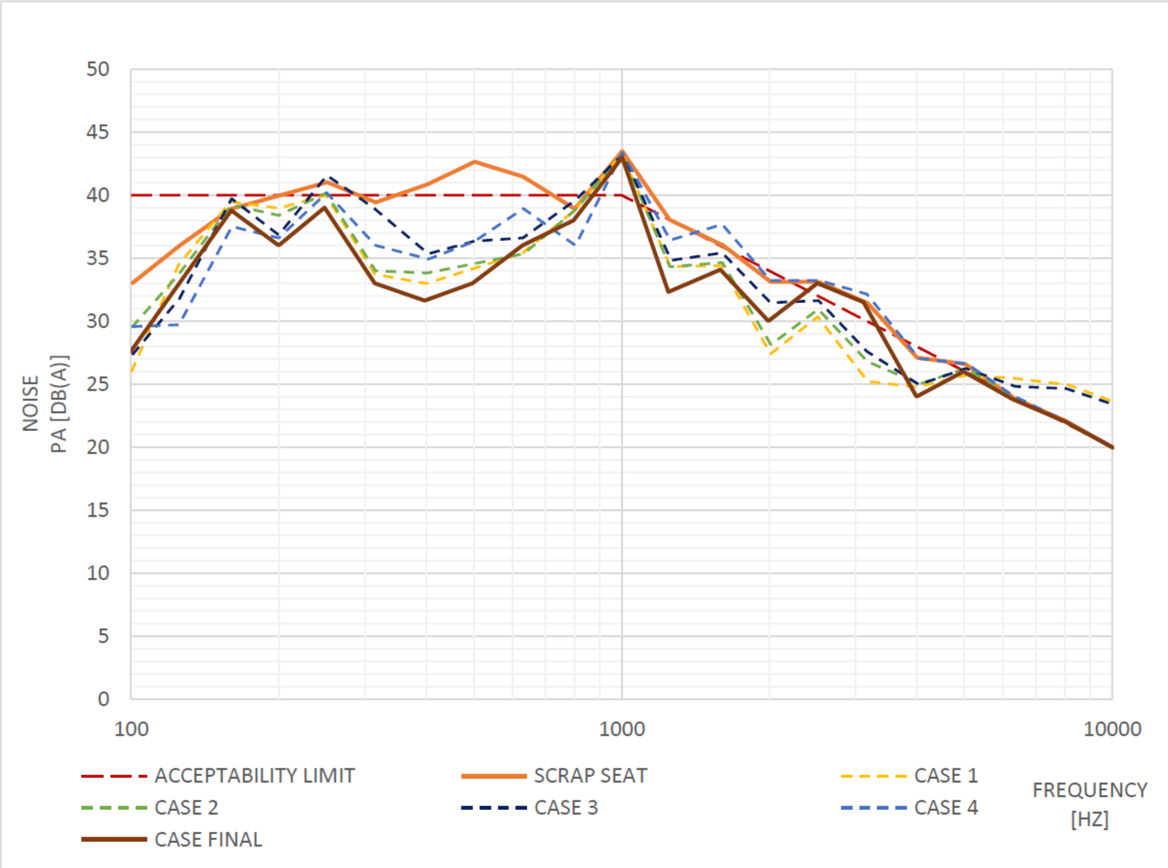

Figure 8.1: Objective Evaluations

Examining the graph above that represents the objective noise evaluation, it is clear that significant noise reduction is achieved across all frequencies, which is a highly positive outcome. This result is particularly remarkable considering the scope of modifications, which included alterations to both critical system parameters and structural components. From a subjective point of view of the evaluation of the final configuration, myself and the technicians of the Sabelt laboratory have filled the SAE rating scale, as it had been done previously in the case of the scrapped seat, in function of the noises that are perceived by our ears and by the hands-on approach, and the result is shown in the figure 8.2 below.

<table>
<tr><td></td><td></td><td colspan="4">UNACCEPTABLE</td><td colspan="6">ACCEPTABLE</td></tr>
<tr><td rowspan="5">CUSTOMER VIEWPOINT</td><td>Judgment</td><td>Very poor</td><td>Poor</td><td>Less than mediocre</td><td>Mediocre</td><td>Acceptable limit</td><td>Acceptable</td><td>Discreet</td><td>Good</td><td>Very good</td><td>Excellent</td></tr>
<tr><td>Detectability</td><td>All customers</td><td colspan="3">Medium customers</td><td colspan="2">Critical customers</td><td colspan="4">Expert customers</td></tr>
<tr><td>Perceptibility</td><td colspan="3">HIGH</td><td colspan="3">MODERATE</td><td colspan="2">SMALL</td><td>VERY SMALL</td><td>NONE</td></tr>
<tr><td>Sensation</td><td colspan="2">Intolerable</td><td>Strong discomfort</td><td>Discomfort</td><td>Slight discomfort</td><td colspan="2">Small disturbance</td><td>Minimal disturbance</td><td colspan="2">No disturbance</td></tr>
<tr><td>Reaction</td><td colspan="2">Refusal</td><td colspan="2">Protest</td><td>Complaint</td><td colspan="2">Acceptance</td><td colspan="2">Appreciation</td><td>Enthusiasm</td></tr>
<tr><td>Alphanumeric scale</td><td>Voting Scale (1-10)</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td><td>6</td><td>7</td><td>8</td><td>9</td><td>10</td></tr>
<tr><td colspan="2">Corrective Actions</td><td colspan="2">Radical and immediate intervention</td><td colspan="3">Timely corrective intervention</td><td>To be improved</td><td colspan="2">Requires attention</td><td colspan="2">OK</td></tr>
</table>

Figure 8.2: Final Case Subjective Evaluation

It was possible to perceive the difference in the seat's noise performance through a subjective evaluation, without the use of a noise measurement tool, but only with hearing and touch. The chosen optimization set was able to change the seat's Judgment from 'Acceptable limit' to 'Discreet', the Perceptibility from 'MODERATE' to 'SMALL', the Sensation from 'Small disturbance' to 'Minimal disturbance', and the Voting Scale from 6 to 7, making the seat 'OK' and without the need of further 'Requires attention'.

8.3 Work Limits

Although the project deliver promising results, several limitations involve further consideration. One key limitation is the simplifying assumptions used during simulations. For instance, the usage of a mono-axial shaker means that certain dynamic interactions and complex real-world conditions are not fully replicated, potentially affecting the precision of the outcomes. Similarly, the experimental tests are conducted in controlled environments, which, while valuable for isolating external test disturbances, may not entirely capture the excitations received by actual vehicle operation. Another area of uncertainty is the long-term performance and durability of the design under different environmental conditions. Factors such as temperature variations, humidity, and prolonged use are not examined in depth, leaving open questions about how the seat might perform over extended periods or in varying scenarios. Finally, the final configuration reflects a pragmatic approach, created to balance technical performance with company constraints. This includes operational considerations, such as manufacturability, cost-effectiveness, and adherence to regulatory standards, which may have limited the exploration of more experimental or unconventional design solutions.
The key criteria that guided this choice are:

- **Cost:** The decision to exclude the tension bar resulted in significant cost savings, avoiding additional expenses related to material procurement and the implementation of new production processes.

- **Assembly Time:** The final configuration was optimized for quick assembly compared to the modifications proposed in Case 2. This reduced per-unit production time, ensuring greater efficiency on assembly lines.

- **Mass Production Feasibility:** All selected components were chosen to guarantee easy integration into existing production lines, eliminating the need for significant changes to manufacturing infrastructure.
- **Aesthetic Appearance:** The tension bar was excluded partly due to aesthetic considerations. While it offered functional advantages, this component would have impacted the interior design of the vehicle, potentially compromising the visual perception of the seat and not aligning with the cockpit's stylistic standards.

However, in a future scenario with fewer economic or time constraints, the possibility of reintroducing the tension bar could be reconsidered to further optimize acoustic performance.

8.4 Personal Reflections

Reflecting on each stage of this project, it has been an immensely gratifying and instructive experience. This case study offered me a unique opportunity to understand how complex systems and methodologies converge to solve a practical problem, integrating theoretical concepts with real-world application. Each phase presented its own challenges, such as the revising prototypes when the test results did not align with the expectations. These obstacles, while demanding, served as opportunities for growth, allowing me to improve my knowledge in the Noise, Vibration and Harshness analysis. The most important characteristics that the technicians and engineers of the Sabelt laboratory transmit to me are the methodology used to approach this kind of analysis and the winning approach with problems that is essential to achieve success.

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Appendix

Stevens' Power Law

[1] Stevens' power law is an empirical relationship in psychophysics between an increased intensity or strength in a physical stimulus and the perceived magnitude increase in the sensation created by the stimulus.

Fourier Transform

[2] The Fourier Transform (FT) is a mathematical technique used to transform a time-domain signal into its frequency-domain representation. It decomposes a signal into a sum of sinusoidal components, each with a specific frequency, amplitude, and phase. This transformation allows us to understand how the signal behaves in the frequency domain, making it easier to analyze its spectral content. It allows to analyze signals in terms of their frequency components rather than their time-domain characteristics.

Power Spectral Density

[3] The PSD of a stationary random process is the Fourier transform of its autocorrelation function. This means that by calculating the Fourier transform of the autocorrelation function, we can determine how power is distributed across different frequencies. In practice, this is critical in vibration analysis, where the PSD reveals the energy distribution of vibrations over time. The autocorrelation function measures the similarity of a signal with a delayed version of itself, and it is often used to characterize signals that are inherently random or noisy. A critical property of the autocorrelation function is that it is even and real-valued, ensuring that the PSD, derived as its Fourier transform, is also real and non-negative, which is physically meaningful (since power cannot be negative). The Fourier transform relationship highlights that the PSD provides a frequency-domain representation of the signal's energy, making it easier to identify dominant frequencies, resonance behavior, and power distribution over time.

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List of Equations

Eq. (2.1) Sound Intensity Vector, I

Eq. (2.2) Sound Pressure Level, SPL

Eq. (2.3) Sound Propagation Speed, v

Eq. (2.4) Equivalent Sound Pressure Level Received, L

Eq. (2.5) Attenuation Factor, A

Eq. (3.1) Power Spectral Density, PSD

List of Symbols

Variable	Description	SI unit
P	Pressure	Pa
p	Sound Pressure	Pa
W	Sound Power	Watt
I	Sound Intensity Vector	W/m^2
r	Distance from the source	m
ρ	Density of the medium	kg/m^3
c	Speed of sound in the medium	m/s
p_{ref}	Reference Sound Pressure	20µPa
SPL	Sound Pressure Level	dB
v	Sound Speed	m/s
B	Bulk Fluid Modulus	MPa
$S_x(f)$	Power Spectral Density	g^2/Hz
$noise$	Noise	Pa dB(A)
f	Frequency	Hz