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Review on the NVH Sources in an Electric Vehicle and Their Respective Contribution in Overall Noise from an Electric Vehicle

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Abstract

NVH, which stands for noise, vibration, and harshness, typically ranks within the top five attributes in terms of priority during the design phase of automotive vehicles. As electric vehicles become increasingly prevalent in modern transportation, the management of Noise, Vibration, and Harshness (NVH) has emerged as a critical aspect of vehicle design and refinement. This review paper aims to provide a thorough examination of the NVH sources within EV powertrains and their respective contributions to the overall noise emitted by electric vehicles. Each NVH source is analyzed in terms of its underlying mechanisms, frequency spectra, and methods for quantification and characterization. By synthesizing existing literature, industry insights, and technological advancements, this review primarily aims to enhance the understanding of NVH challenges in electric propulsion systems and facilitate the development of quieter and more refined electric vehicles.

Keywords: NVH, Electric Vehicle, Whine, Gear Micro Parameters, MOTOR-INDUCED VIBRATIONS.

INTRODUCTION

In the rapidly evolving landscape of Automotive Engineering, the advent of electric powertrains has marked a pivotal shift towards sustainability and efficiency in the transportation sector. With the rise of electric vehicles, a new realm of engineering challenges and opportunities has emerged, one of which is the intricate domain of NVH management. NVH encompasses the complex interplay of noises, vibrations, and harshness levels that vehicles generate during operation [1]. While conventional internal combustion engines have long been the primary focus of NVH mitigation strategies, the transition to electric powertrains brings forth a unique set of NVH characteristics that demand specialized attention. Unlike their traditional counterparts, electric powertrains operate with distinct mechanisms and components, such as electric motors, power inverters, and battery packs, each contributing to the overall NVH profile of the vehicle. The absence of internal combustion processes, coupled with the inherent smoothness of electric motors, introduces novel challenges in identifying, analyzing, and mitigating NVH phenomena in electric vehicles. Furthermore, the silent operation of electric powertrains amplifies the perceptibility of otherwise subtle vibrations and noises, thereby necessitating heightened NVH refinement to meet the discerning expectations of modern consumers. Addressing NVH concerns in electric vehicles is not merely a matter of comfort and luxury but also crucial for ensuring user satisfaction, safety, and regulatory compliance. In this context, understanding the intricacies of NVH

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in electric powertrains becomes imperative for automotive engineers, designers, and manufacturers alike. This necessitates the development of innovative methodologies, simulation techniques, and experimental approaches tailored to the unique NVH characteristics of electric vehicles. The work done by Jiri Tuma [28], J.D. Welbourn [2], R.C. Fazer [10] and Ulrich Kissling [15, 35, 36] are notable in the field of NVH refinement by optimizing gear micro geometries. Also the work done by Mats Åkerblom [42, 43] during his PhD is worth highlighting and becomes the foundation for this paper. The survey done by Mohammad Qatu [32] explains the recent works done to reduce the NVH. But the inspiration for writing this paper is the recent boom in the demand of electric vehicles in the market, challenging to mitigate those noises which were got suppressed in IC engine vehicle, by the noise generated due combustion inside the cylinder and relative motion between several engine components. This paper is written as a source of complete NVH guide for those who wants to work in this field of NVH mitigation of electric vehicles, they can get understating of the sources and mechanisms generating NVH in electric vehicles and basic idea of how to attenuate it [3–9]. Also NVH testing should be done in anechoic chamber and test track it is tedious and complicated process which requires many variables and testing parameters to be controlled, therefore some software platforms are also explained in this paper for virtual testing of electric vehicle NVH.

SOURCES

Motor-induced Vibrations: IN electric vehicles motor-induced vibrations represent a significant contributor to NVH challenges. These vibrations emanate primarily from the electric motor, which serves as the propulsion source in electric vehicles. As the motor operates, it generates torque and rotational motion, causing mechanical vibrations that propagate through the vehicle structure [11–18]. The frequency and magnitude of these vibrations depend on various factors, including motor design, mounting configuration, and operational conditions. Additionally, motor-induced vibrations can interact with other vehicle components, amplifying NVH issues throughout the vehicle. Motor induces vibrations introduce unique vibrational characteristics into the vehicle’s operational dynamics. The transition to electric powertrains brings forth a paradigm shift in NVH considerations, necessitating a thorough understanding of the sources, mechanisms, and implications of motor-induced vibrations in electric vehicles. The noise comes from the vibrations of the electric motor in the audible range under the excitation of electromagnetic forces, including magnetostriction and Maxwell forces. Loose Bearings and loose Mountings and damaged paddings are the mechanical reasons behind the motor induced vibrations to be generated and propagated through the vehicle structure [19–27].

- o *Electro-Magnetic Forces:* Electromagnetic forces represent the fundamental interactions stemming from the relationship between electrically charged particles and magnetic fields. These forces govern various natural phenomena, including the attraction and repulsion between charged particles, the dynamics of electromagnetic fields, and the propagation of noise [29–31].

The four mechanisms responsible for generating electromagnetic forces (EM forces) are:

- The result of slotting is the initial mechanism of force creation. This is the result of the permanent magnet placement pattern in the rotor, winding slots, and evenly spaced stator teeth. The two main outcomes of the slotting are:
    1. The magnetomotive force (MMF) is disrupted along the circle of the air gap, which causes high harmonic content to superimpose on top of the fundamental MMF wave.
    2. The air gap is a representation of the magnetic circuit’s overall resistance. When the relative positions of the stator and rotor vary, winding slots cause the uniform cylindrical shape of the air gap around its perimeter to be disrupted, hence periodically changing the reluctance of the magnetic circuit. The tooth-faces-magnet and slot-faces-slot local maximum and minimum permeance values, respectively, correspond to these combinations.
- Iron magnetic saturation is the second process for force generation. This results in an uneven distribution of magnetic flux, which in turn produces more harmonics in the electromagnetic force.

- The third cause relates to harmonics generated by pulse-width modulation (PWM) techniques, which are employed to achieve desired frequency and amplitude, and are present in the motor voltage supply. The electromagnetic force encircling the air gap exhibits these harmonics [33–41].
- Rotor and stator eccentricity is the fourth mode of force generation. Significant relative distortion of air gap permeance occurs from even a small departure of the air gap from a uniformly thick cylindrical sleeve shape, leading to the production of harmonics. It is important to note that eccentricity's impacts are not taken into consideration by this thesis.

Elevated above the weak nuclear force, strong nuclear force, and gravity as the four fundamental forces of existence, electromagnetic forces are defined by Maxwell's equations, which characterize the behaviour of electric and magnetic fields [2].

Four basic equations known as Maxwell's equations explain how electric and magnetic fields behave in classical electromagnetism. In this form, they are differential:

- Gauss' s Law for Electricity:

$$\nabla. \mathrm{E} = \frac{\rho}{g_0}$$

- Gauss's Law for Magnetism:

$$\nabla \cdot \mathrm{B} = 0$$

- Faraday's Law of Electromagnetic Induction:

$$\nabla \times \mathrm{E} = \frac{\partial B}{\partial t}$$

- Ampère's Circuital Law with Maxwell's Addition (Ampère-Maxwell Law):

$$\nabla \times \mathrm{E} = \mu_0 J + \mu_0 \varepsilon_0 \frac{\partial B}{\partial t}$$

    - *Magnetostriction:* Magnetostriction refers to the property exhibited by certain materials, notably ferromagnetic ones like iron or nickel, where they undergo changes in shape or size when subjected to a magnetic field. This phenomenon occurs due to the realignment of the material's atomic or molecular structure in response to the applied magnetic field. As a result, the material may experience alterations in its dimensions, volume, or shape. Magnetostriction finds applications in various fields, including the development of sensors, actuators, and transducers, where the interaction between magnetic fields and materials is utilized, but in EV's this property results in unwanted noise and vibrations.

Furthermore, the dynamic nature of electric motor operation, particularly during acceleration, deceleration, and regenerative braking, introduces transient vibrational events that can exacerbate NVH issues. These transient vibrations, coupled with resonance effects within the vehicle structure, contribute to perceptible noise and discomfort for vehicle occupants [44–50].

Transaxle Whine Noise: UNLIKE conventional vehicles with internal combustion engines, electric vehicles feature unique drivetrain configurations, often employing single-speed or multi-speed transmissions integrated with electric motors in a compact transaxle assembly. While this integration optimizes efficiency and performance, it also introduces the potential for transaxle whine noise, characterized by high-pitched, tonal sounds that may be perceptible to vehicle occupants and bystanders.

Transaxle whine noise in electric vehicles stems from various factors, including gear meshing dynamics, bearing interactions, and resonance phenomena within the drivetrain components. The design and operation of electric motor-transaxle assemblies, coupled with the high torque and rotational speeds inherent to electric propulsion systems, can exacerbate the occurrence and transmission of whine noise throughout the vehicle structure.

The pursuit of superior NVH performance in electric vehicles necessitates a comprehensive understanding of transaxle whine noise and its underlying mechanisms. NVH engineers employ advanced simulation, modeling, and experimental techniques to analyze and mitigate whine noise, optimizing gear tooth profiles, bearing configurations, and damping strategies to minimize its impact on vehicle refinement and occupant comfort.

The Primary culprits causing Transaxle whine are Transmission Error in gears, insufficient contact ratio of mating gears, gear profile, inefficient lubrication, poor backlash; i.e. All the micro and macro parameters of gears are main reason behind transaxle whine in electric vehicles [52–55].

- *Transmission Error:* Gear whining is a sort of gear noise that is mostly caused by vibrations caused by transmission errors. According to Welbourn [2], transmission error is the motion error that results from the discrepancy between the actual position of the output gear and its position if the gear teeth were perfectly shaped and infinitely rigid [2].

Transmission error (TE) is defined as:

$$TE = R_{bg}\left[\theta_p - \frac{N_g}{N_p}\theta_g\right]$$

Where, θ_p and θ_g are the rotations of the pinion and gear shafts, and Np and Ng are the Number of teeth on the pinion and gear, respectively. R_{bg} is the base radius of the pinion.

The causes of transmission error are deflections, geometrical errors and geometrical modifications. Examples of deflections: bearing and gearbox casing flexibility, contact deformations (hertzian) in the gear mesh, gear blank deflections, gear teeth bending deflections, shaft deflections. Examples of geometrical errors: involute alignment deviations, involute form deviations, lead deviations, lead form deviations, gear tooth bias, pitch errors, run-out, error in bearing position in the casing. Examples of some common geometrical modifications: lead crowning, helix angle modification, profile crowning, tip relief and root relief [42].

Errors in manufacture and assembly as well as elastic deflections in gear teeth, shafts, bearings, and housing are the main sources of transmission error. Error in transmission is thus torque dependent.

- *Contact Ratio:* The contact ratio of gears serves as a crucial metric to assess the degree of tooth engagement during gear operation. It holds significance in gear design and analysis, primarily for evaluating the smoothness of gear motion, distributing loads effectively, and minimizing noise.

The contact ratio is typically defined as the ratio of the length of the arc of action to the circular pitch of the gear teeth. In other words, it represents the fraction of time during a gear revolution that at least one pair of teeth is in contact [56–57].

$$CR = \frac{\sqrt{r_{ap}^2 + r_p^2} + \sqrt{r_{ag}^2 + r_g^2} + C\,sin\,\emptyset}{p_b} = \frac{\text{Length of Arc of Action (L)}}{\text{Circular Pitch}}$$

Where, r_{ap} is addendum radius of pinion gear and r_p is the pitch circle radius of pinion similarly r_{ap} and r_p respective radiuses for gear. C is the centre distance between the gear and pinion wheels. ∅ is the pressure angle of gear and wheel Pb is the circular pitch which is defined as:

$$p_b = \frac{\pi \times d}{z}$$

Where, d is the pitch circle diameter of gear and Z is the no. of teeth of gear.

A higher contact ratio generally indicates smoother and quieter operation, as it ensures a more continuous transfer of load between the mating gear teeth. It also helps distribute the load more evenly across the gear teeth, reducing wear and the risk of premature failure.

Designing gears with an appropriate contact ratio involves balancing factors such as tooth geometry, pitch, and the desired level of smoothness and load distribution for the specific application. Different gear profiles and modifications can be employed to optimize the contact ratio based on the requirements of the gear system.

- *Tooth Profile:* The gear tooth profile refers to the specific shape and geometry of the teeth on a gear. It plays a crucial role in the proper functioning and performance of gears in transmitting rotational motion and power between shafts.

The specific tooth profile chosen for a gear depends on factors such as the application, load requirements, speed, and efficiency considerations. Proper design and manufacturing of the tooth profile are essential to ensure smooth meshing, efficient power transmission, and minimal wear over the gear’s lifespan.

Profile correction on gears is one of the most common techniques used to reduce transmission errors, contact shock and scoring risk. Types of profile correction there are several types of profile corrections on gears. It is a well-known fact that the profile correction used will significantly affect the resulting transmission error [39]. Following tooth profile modification formula is obtained by TZaoping Tang et.al for minimal noise generation [39]:

$$C_{\theta} = \frac{K_A K_{mp} F_t}{b \cos \alpha_t C_{\gamma}}$$

Where, b is the tooth width (unit: mm), at is the end pressure angle, Ft is the end face tangential force on the indexing cylinder (unit: N), KA is the service factor, Kmp is the branching coefficient, T is the torque (unit: Nm), and Cγ is the comprehensive stiffness of the tooth (unit: N (mm. μm)) [36].

Profile correction includes applying teeth relief, crowning of teeth, root diameter correction and helix angle modification.

- *Backlash:* Gear backlash pertains to the clearance or play existing between the teeth of engaged gears within a gear system. This space between tooth profiles allows for movement before contact occurs.

In gear systems, backlash is a crucial factor influencing precision, accuracy, and the smoothness of motion transmission. While a certain level of backlash is necessary to account for manufacturing variations, thermal effects, and lubrication, excessive backlash can lead to undesirable outcomes such as noise, vibrations, and decreased efficiency.

The measurement of backlash is typically expressed as the distance between engaged teeth along the pitch circle diameter when the gears are disengaged. This measurement can be specified in linear terms (e.g., millimetres or inches) or as an angular value (e.g., degrees of rotation).

To optimize gear system performance, it’s important to carefully design and assemble gears, considering factors like gear types, tooth profiles, and manufacturing tolerances. Periodic maintenance and adjustments may also be required to ensure the gear system operates effectively and has a prolonged lifespan.

Electro-Magnetic Noise: IN contrast to traditional internal combustion engine vehicle, electric vehicles rely on electric motors and power electronics to propel them. While these electric propulsion systems offer numerous advantages, including efficiency and reduced emissions, they also introduce electromagnetic noise as a by-product of their operation. This electromagnetic noise arises from the interaction of electric currents and magnetic fields within the motor windings, power converters, and associated electrical components. Squeal or a chatter from the shaft or housing of an electric motor are the form of electromagnetic noise.

The electromagnetic forces contain a prime component at the frequency of rotation called first harmonic, it also include variations that are produced at higher frequencies which are multiples of the first harmonic and can contribute significantly in the NVH performance of a motor.

Motors experiences electromagnetic forces that are not purely sinusoidal. The sources of electromagnetic noise in electric vehicles are diverse and complex, encompassing various phenomena such as switching transients in power electronics, magnetic field interactions, and electromagnetic interference (EMI) propagation through vehicle wiring and communication networks. Electromagnetic interference refers to undesired disturbances or noise in an electrical pathway or circuit resulting from external sources. Commonly termed as radio frequency interference, EMI has the potential to impair the performance of electronics, leading to operational deficiencies, malfunctions, or complete failure. EMI can be caused by either natural or human-made reasons. The broad frequency spectrum of electromagnetic noise, spanning from low-frequency magnetic fields to high-frequency radio frequencies, presents challenges for NVH engineers tasked with mitigating its impact on vehicle performance and occupant comfort.

EMI arises from the intimate connection between electricity and magnetism. Whenever electricity flows, it generates a minor magnetic field, and conversely, a moving magnetic field induces an electrical current. These fundamental principles underlie the functionality of electric motors and generators. Moreover, any electrical conductor can function as a radio antenna. Powerful electrical and radio emitters can produce adverse impacts on distant devices. As electronics advance in miniaturization, speed, density, and sensitivity, they become increasingly vulnerable to these influences, thereby exacerbating EMI concerns. All these conditions for EMI generation is available inside the Electric Motor of EV.

The proliferation of electric propulsion systems in electric vehicles underscores the importance of understanding and addressing electromagnetic noise. Effective strategies for mitigating electromagnetic noise include the implementation of electromagnetic shielding, filtering techniques, and careful design considerations to minimize EMI propagation paths. Use of high quality of electronics and PMSM motors can be referred as the potential solution for the electromagnetic noise from an electric vehicle power train.

The propagation of sound within a three-dimensional space can be mathematically represented in the frequency domain by the Helmholtz partial differential equation as: [51]

$$\nabla^2 \mathrm{p} + k^2 p = \sum_{K=t}^{N_S} Q_k \, \delta(\xi_k^f, \xi)$$

Where $\nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}$, p is the acoustic pressure, $k = \frac{\omega}{c}$, $\omega = 2\pi f$, f is the frequency, c is the sound propagation velocity within the acoustic medium, N_S is the number of sources in the domain, Q_k is the magnitude of the existing sources ξ_k^f located at $\left(x\xi_k^f,\ y\xi_k^f,\ z\xi_k^f,\right)$, ξ domain point located at (x_ξ, y_ξ, z_ξ) and $\delta\left(\xi_k^f, \xi\right)$ is the Dirac Delta Function [51].

In the above defined Helmholtz equation, the Somerfield radiation condition $\lim_{x\to 0}\left(\frac{\partial p}{\partial n}\right)\mathrm{ikp(X)} = 0$ is automatically satisfied at infinity, where X is the field point located at (x, y, z), n is the unit outward normal vector and $i = \sqrt{-1}$ [51].

Tire-road Interaction

TIRE-road interaction noise encompasses the audible vibrations and sound emissions generated as the vehicle's tires make contact with the road surface during driving. Unlike traditional internal combustion engine vehicles, electric vehicles often feature unique tire and road interaction characteristics influenced by factors such as tire composition, tread pattern, road surface texture, and electric motor dynamics.

The transition to electric propulsion systems introduces nuances in tire-road interaction noise due to the instantaneous torque delivery and regenerative braking capabilities inherent to electric motors. These dynamics affect tire grip, wheel slip, and road adherence, influencing the intensity and frequency distribution of noise generated during acceleration, deceleration, and cornering manoeuvres.

Furthermore, the quiet operation of electric motors accentuates tire-road interaction noise, making it more perceptible to vehicle occupants and bystanders. As such, tire-road interaction noise plays a significant role in shaping the overall NVH performance and perceived quality of electric vehicles, impacting driver comfort, cabin acoustics, and exterior noise emissions.

Addressing tire-road interaction noise in electric vehicles requires a multifaceted approach, encompassing tire design optimization, road surface engineering and NVH refinement techniques. Advanced simulation, modelling and experimental methodologies enable NVH engineers to analyse and mitigate tire-road interaction noise, optimizing tire compositions, tread patterns, and vehicle suspension systems to minimize unwanted noise and vibration.

Aerodynamic Noise: THE quiet operation of electric motors accentuates the prominence of aerodynamic noise in electric vehicles, heightening the importance of aerodynamic refinement in achieving superior NVH performance. As electric vehicles strive for increased range and efficiency, minimizing aerodynamic drag and associated noise becomes a critical engineering challenge. This issue is present in the ICE vehicles also but there it got suppressed by the noise generated due the engine combustion and transmission noise, but in EV where powertrain is very silent as compare to the ICE vehicle powertrain aerodynamic noise has become a very prominent contributor to overall noise.

Aerodynamic noise encompasses the acoustic disturbances generated by the interaction of airflow with the vehicle's exterior surfaces during motion. Unlike traditional internal combustion engine vehicles, electric vehicles often feature streamlined designs and reduced mechanical noise emissions, making aerodynamic noise more perceptible to vehicle occupants and bystanders. The transition to electric propulsion systems introduces novel aerodynamic dynamics, influenced by factors such as vehicle shape, frontal area, wheel arches, side mirrors, and underbody airflow management.

Among the array of NVH challenges specific to electric vehicles, aerodynamic noise emerges as a significant consideration, influencing vehicle refinement, efficiency, and overall driving experience.

Brake Noise: BRAKE noise encompasses the audible disturbances generated during braking manoeuvres, originating from the interaction between brake components such as brake pads, rotors, callipers, and the surrounding environment. While brake noise is a prevalent issue in all vehicles, the unique characteristics of electric propulsion systems present distinctive challenges and considerations for electric vehicles brake systems.

Unlike conventional internal combustion engine vehicles, electric vehicles often feature regenerative braking systems that harness kinetic energy during deceleration to recharge the vehicle's battery. The integration of regenerative braking introduces new dynamics into the braking process, including variations in brake force distribution, friction characteristics, and thermal management, which can influence the occurrence and intensity of brake noise.

Moreover, the inherently quiet operation of electric motors in electric vehicles amplifies the perceptibility of brake noise, making it more noticeable to vehicle occupants and pedestrians. As EV manufacturers prioritize vehicle refinement and user experience, addressing brake noise becomes paramount to ensuring driver confidence, passenger comfort, and overall NVH performance.

Ancillary Components: ANCILLARY components in an electric vehicle encompass a wide array of systems beyond the core electric motor and battery, including but not limited to cooling systems, auxiliary pumps, power electronics, and thermal management units. These components, essential for maintaining optimal operating conditions, introduce unique acoustic signatures and challenges within the acoustic landscape of electric vehicles.

The quiet operation of electric motors in electric vehicles accentuates the perceptibility of ancillary component noise, making their acoustic contributions more noticeable to occupants and bystanders alike. The management of ancillary component noise is pivotal not only for enhancing the passenger experience within the vehicle cabin but also for mitigating external noise emissions, contributing to the overall acoustic footprint of electric vehicles in urban environments.

Addressing ancillary component noise requires a comprehensive approach that involves innovative design strategies, advanced materials, and sophisticated NVH refinement techniques. Engineers must consider the integration of sound insulation materials, strategic placement of components, and the development of efficient and acoustically optimized ancillary systems.

ATTENUATION OF NOISE AND VIBRATION

Motor-induced Vibrations: THE complexity of motor-induced vibrations in electric vehicles necessitates a multifaceted approach to NVH management. Engineers deploy a variety of methods and technologies to mitigate vibration levels and enhance overall vehicle refinement. These methods encompass both passive and active solutions, leveraging advancements in materials science, structural design, and vibration control systems.

Passive methods for reducing NVH due to motor-induced vibrations include the optimization of motor mounting systems, utilization of vibration-damping materials, and implementation of structural reinforcements to minimize the transmission of vibrations to the vehicle chassis and cabin. By strategically isolating the motor from the vehicle structure and attenuating vibrational energy, passive solutions help enhance passenger comfort and reduce intrusive noise levels.

In addition to passive techniques, active vibration control systems offer dynamic solutions to mitigate motor-induced vibrations in real-time. These systems utilize sensors and actuators to detect and counteract vibrations, effectively cancelling out undesirable oscillations and harmonics. Active vibration control algorithms adjust phase and amplitude to achieve optimal vibration attenuation, providing a tailored NVH solution that adapts to changing driving conditions.

Moreover, advancements in computational modelling and simulation enable engineers to predict and optimize NVH characteristics during the design phase, facilitating the development of quieter and more refined electric vehicles. By integrating simulation-driven design methodologies, manufacturers can expedite the NVH optimization process and achieve superior vehicle performance without compromising development timelines.

Transaxle Whine Noise: THE quiet operation of electric motors accentuates the perceptibility of transaxle whine in electric vehicles, making it more noticeable to vehicle occupants and passengers. As a result, mitigating transaxle whine noise becomes a critical aspect of NVH refinement efforts, aimed at enhancing cabin comfort and overall driving satisfaction.

Addressing transaxle whine in electric vehicles requires a multifaceted approach that leverages advanced engineering techniques and innovative solutions. Passive methods for reducing whine noise include optimizing gear tooth profiles, enhancing bearing designs, and refining lubrication systems to minimize friction and vibration within the transaxle assembly. Additionally, strategic placement of sound-absorbing materials and acoustic insulation helps attenuate noise transmission paths, effectively damping unwanted vibrations and reducing perceived noise levels.

Active noise cancellation systems represent a dynamic solution to mitigate transaxle whine noise in real-time. These systems utilize microphones and speakers strategically placed within the vehicle cabin to detect and counteract whine frequencies, effectively canceling out undesirable noise and enhancing passenger comfort.

Electro-magnetic Noise: ADDRESSING electro-magnetic noise in electric vehicles requires a multifaceted approach that encompasses various engineering disciplines and advanced technologies. Passive methods for reducing electro-magnetic noise include the optimization of motor design parameters such as rotor-stator configurations, winding layouts, and magnetic field control strategies to minimize EMI and associated noise emissions.

Additionally, the strategic placement of electromagnetic shielding materials and insulation techniques helps attenuate noise transmission paths, effectively damping unwanted electro-magnetic vibrations and reducing perceived noise levels. Furthermore, advancements in power electronics design enable the implementation of switching strategies and modulation techniques to reduce harmonics and transient disturbances, mitigating electro-magnetic noise at its source.

Active noise cancellation systems represent a dynamic solution to mitigate electro-magnetic noise in real-time. These systems utilize sensors and actuators to detect and counteract noise frequencies, effectively canceling out undesirable noise and enhancing passenger comfort.

Tire-road Interaction Noise: TIRE road interaction noise in electric vehicles requires a multifaceted approach that leverages advanced engineering techniques and innovative solutions. Passive methods for reducing tire-road interaction noise include optimizing tire designs to minimize tread pattern noise, enhancing road surface characteristics to reduce rolling resistance and noise emissions, and employing sound-absorbing materials within the vehicle cabin to attenuate noise transmission paths.

Furthermore, advancements in tire and road surface technologies enable the development of low-noise tire compounds and innovative road construction materials designed to mitigate tire-road interaction noise while maintaining optimal traction and handling characteristics. Active noise cancellation systems represent a dynamic solution to mitigate tire-road interaction noise in real-time. These systems utilize microphones and speakers strategically placed within the vehicle cabin to detect and counteract noise frequencies, effectively cancelling out undesirable noise and enhancing passenger comfort.

Aerodynamic Noise: PASSIVE methods for reducing aerodynamic noise include optimizing vehicle body contours to minimize air turbulence and drag, enhancing aerodynamic features such as spoilers and diffusers to streamline airflow, and employing sound-absorbing materials within the vehicle cabin to attenuate noise transmission paths. Furthermore, advancements in computational fluid dynamics (CFD) simulations and wind tunnel testing enable engineers to analyse and optimize aerodynamic characteristics during the vehicle design phase, facilitating the development of quieter and more aerodynamically efficient electric vehicles. Active noise cancellation systems represent a dynamic solution to mitigate aerodynamic noise in real-time. These systems utilize microphones and speakers strategically placed within the vehicle cabin to detect and counteract noise frequencies, effectively cancelling out undesirable noise and enhancing passenger comfort.

Moreover, advancements in materials science enable the development of lightweight and acoustically optimized components designed to reduce noise emissions while maintaining structural integrity and durability. By integrating passive and active noise mitigation techniques with advanced simulation methodologies, manufacturers can achieve superior NVH performance in electric vehicles, enhancing driving experiences and passenger comfort.

Brake Noise: AMONG the diverse array of NVH challenges encountered in electric vehicles, brake noise stands out as a significant concern, influencing both vehicle safety and occupant comfort. Passive methods for reducing brake noise include optimizing brake pad materials to minimize vibration and noise generation, refining rotor and calliper designs to enhance damping characteristics, and employing sound-absorbing materials within the brake assembly to attenuate noise transmission paths.

Furthermore, advancements in brake system design enable the implementation of noise-reducing features such as chamfered edges, slotting, and cross-drilling to mitigate brake squeal and minimize high-frequency noise emissions. Active noise cancellation (ANC) systems represent a dynamic solution to mitigate brake noise in real-time.

Moreover, advancements in computational modelling and simulation enable engineers to predict and optimize NVH characteristics during the design phase, facilitating the development of quieter and more refined brake systems for electric vehicles. By integrating passive and active noise mitigation techniques with advanced simulation methodologies, manufacturers can achieve superior NVH performance in electric vehicles, enhancing driving experiences and passenger comfort.

Ancillary Components: IN electric vehicles, ancillary noise is influenced by a multitude of factors, including component design, placement, operational dynamics, and interaction with the vehicle structure. Passive methods for reducing ancillary noise include optimizing component design to minimize vibration and noise generation, refining materials and manufacturing processes to enhance damping characteristics, and employing sound-absorbing materials within the vehicle cabin to attenuate noise transmission paths. Furthermore, advancements in component integration and system optimization enable the development of quieter and more efficient ancillary systems for electric vehicles. Active noise cancellation (ANC) systems represent a dynamic solution to mitigate ancillary noise in real-time.

PLATFORMS AVAILABLE FOR NVH SIMULATION

ROMAX: ROMAX stands for Rotating Machine Experts, it is developed by Hexagon Technologies. Romax provides different modules for strength, modal and acoustic analysis of the system. One can check the transmission error, tooth profile of gears and can optimise it and check the associated noise with it.

LMS Virtual.Lab NVH: LMS Virtual.Lab NVH is a comprehensive software package that enables engineers to simulate and analyse NVH characteristics of complex mechanical systems. It offers modules for modal analysis, frequency response analysis, and acoustic simulation, allowing for detailed NVH assessments across various automotive and aerospace applications.

ANSYS Mechanical: ANSYS Mechanical is a powerful finite element analysis (FEA) software suite that includes modules for structural analysis, modal analysis, and acoustic simulation. Engineers can use ANSYS Mechanical to predict and optimize NVH behaviour in automotive, aerospace, and other mechanical systems.

Siemens Simcenter Amesim: SIEMENS Simcenter Amesim is a multi-domain simulation software platform that offers capabilities for modelling and simulating dynamic systems, including NVH analysis. It enables engineers to explore the interaction between mechanical, electrical, hydraulic, and thermal systems, making it suitable for comprehensive NVH simulations.

COMSOL Multiphysics: COMSOL Multiphysics is a versatile simulation software package that supports multiphysics modelling and simulation, including NVH analysis. It offers a user-friendly interface and a wide range of physics modules, allowing engineers to model complex NVH phenomena and explore different design scenarios.

MSC Nastran: MSC Nastran is a widely used finite element analysis (FEA) software package that includes modules for structural dynamics, modal analysis, and acoustics. It provides advanced capabilities for NVH simulation and optimization, making it suitable for a variety of industries, including automotive, aerospace, and mechanical engineering.

Altair HyperWorks: ALTAIR HyperWorks is a comprehensive simulation platform that offers modules for structural analysis, vibration analysis, and acoustic simulation. It provides advanced tools for NVH analysis and optimization, allowing engineers to improve the NVH performance of complex mechanical systems.

Optimus: OPTIMUS is a process integration and design optimization (PIDO) software platform that integrates with various simulation tools, including those used for NVH analysis. It enables engineers to automate the design exploration and optimization process, helping to improve NVH performance while reducing development time and cost (Figure 1).

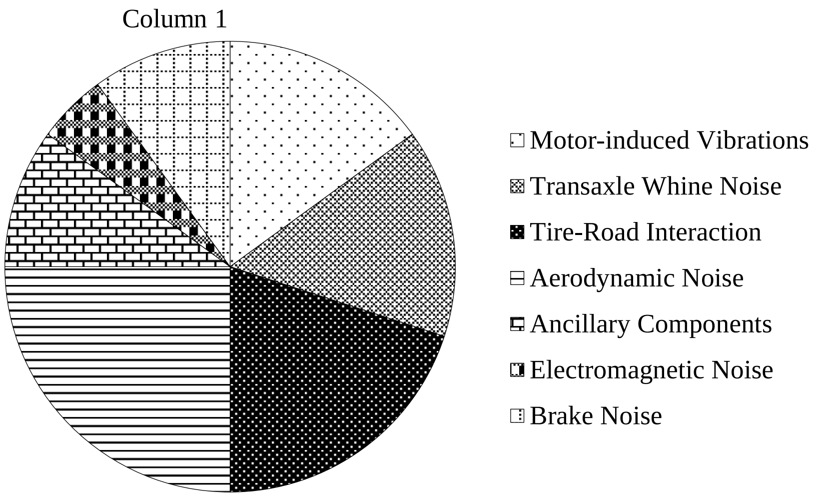

Figure 1. Total NVH Performance of an Electric Vehicle.

CONCLUSION

IN conclusion, our review paper delves deeply into the intricate technical facets surrounding the Noise, Vibration, and Harshness sources entrenched within the powertrain of electric vehicles and their nuanced contributions to the overall acoustic landscape of electric vehicles. Through an exhaustive examination of scholarly literature, empirical research, and industry insights, several pivotal conclusions can be drawn regarding the NVH dynamics of electric vehicles.

Primarily, the novel configuration of EV powertrains introduces a distinct set of NVH challenges compared to conventional internal combustion engine vehicles. While electric vehicles inherently boast quieter operation owing to the absence of engine noise, they remain susceptible to a myriad of alternative sources of noise and vibration. These encompass motor-induced vibrations, transmission whine, tire-road interaction noise, aerodynamic noise, ancillary component noise, electromagnetic noise, and brake noise.

Furthermore, the relative significance of each NVH source in molding the overall noise signature of an EV is contingent upon a multifaceted interplay of factors, spanning vehicle architecture, operational conditions, and environmental variables. Motor-induced vibrations and transmission whine often emerge as predominant contributors, alongside tire-road interaction noise and aerodynamic noise, which become more pronounced at elevated velocities. Ancillary component noise, electromagnetic noise, and brake noise also exert substantial influence on the NVH landscape of electric vehicles.

Addressing NVH intricacies in electric vehicles mandates a holistic approach that amalgamates passive and active noise mitigation techniques, advanced simulation methodologies, and optimization strategies. Engineers grapple with the complex task of reconciling performance imperatives with considerations of weight reduction, cost-effectiveness, and energy efficiency while elevating NVH performance to align with consumer expectations for comfort and refinement.

In summary, our review underscores the pivotal imperative of comprehensively understanding and adeptly managing NVH sources within the powertrain of electric vehicles. By pinpointing and remedying key sources of noise and vibration through innovative engineering interventions, manufacturers can elevate the overall driving experience, foster heightened consumer acceptance of electric vehicles, and propel the transition towards sustainable mobility paradigms. Persistent research and innovation in NVH engineering remain instrumental in propelling the evolution of quieter, more comfortable, and environmentally conscientious electric vehicles in the foreseeable future.

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