World Electric Vehicle Journal

MDPI

Review

Simulating Noise, Vibration, and Harshness Advances in Electric Vehicle Powertrains: Strategies and Challenges

Krisztián Horváth * and Ambrus Zelei

Department of Whole Vehicle Engineering, Széchenyi István University, Egyetem tér 1, H-9026 Győr, Hungary; zelei.ambrus.miklos@ga.sze.hu

* Correspondence: horvath.krisztian@ga.sze.com; Tel.: +36-203154841

Abstract: This study examines the management of noise, vibration, and harshness (NVH) in electric vehicle (EV) powertrains, considering the challenges of the automotive industry's transition to electric drivetrains. The growing popularity of electric vehicles brings new NVH challenges as the lack of internal combustion engine noise makes drivetrain noise more prominent. The key to managing NVH in electric vehicle powertrains is understanding the noise from electric motors, inverters, and gear systems. Noise from electric motors, mainly resulting from electromagnetic forces and high-frequency noise generated by inverters, significantly impacts overall NVH performance. This article details sources of mechanical noise and vibration, including gear defects in gear systems and shaft imbalances. The methods presented in the publication include simulation and modeling techniques that help identify and solve NVH difficulties. Tools like multi-body dynamics, the finite element method, and multi-domain simulation are crucial for understanding the dynamic behavior of complex systems. With the support of simulations, engineers can predict noise and vibration challenges and develop effective solutions during the design phase. This study emphasizes the importance of a system-level approach in NVH management, where the entire drivetrain is modeled and analyzed together, not just individual components.

Keywords: EV powertrain; NVH; noise; acoustic simulation; noise reduction

check for updates

Citation: Horváth, K.; Zelei, A. Simulating Noise, Vibration, and Harshness Advances in Electric Vehicle Powertrains: Strategies and Challenges. *World Electr. Veh. J.* **2024**, *15*, 367. https://doi.org/10.3390/wevj15080367

Academic Editor: Joeri Van Mierlo

Received: 29 June 2024
Revised: 9 August 2024
Accepted: 12 August 2024
Published: 14 August 2024

1. Introduction

Over the last 15 years, electric vehicle (EV) sales have been on a steep upward trajectory. EV-Volumes reports that 541,780 new plug-in electric cars were registered globally in February 2022, more than double the total from February 2021 [1]. In addition to this, Virta's published report of a total of1.06 million new EVs in Europe during the first half of 2021 was a big leap compared with 413,000 for the first half of 2020. This growth, to a great extent, has been caused by bold zero emission goals announced by major global EV markets in the EU, Asia, and the US [2–4].

EVs are a whole new can of worms when it comes to managing noise, vibration, and harshness (NVH) compared to the world of internal combustion engines (ICEs). With no ICE to mask the noise of transmission, and especially when dealing with the constant torque and higher speeds of electric motors, gear design had to improve. The new powertrain technology has implications for sound, and engineers need to consider factors like road noise. However, the most substantial impact will arguably be on the overall noise profile of EVs. The engine side of the powertrain typically has two-stage, non-switchable transmission; the electric side of the powertrain has an upper limit imposed by sufficiently high engine speeds and torque management needs [5].

The challenge in developing new engines and electric driveline architectures specifically for Hybrid Electric Vehicles (HEVs) and Battery Electric Vehicles (BEVs) is even greater. New driveline connections bring their own potential issues and high-frequency challenges for engineers. Compounding the complexity is that electric motors behave differently from uneven gasoline engines, and it is the interactions of components, particularly vibration-related NVH issues, that are tested. These kinds of complex systems call for an understanding of relationships between components [6].

In dealing with NVH for EVs, the challenge is to know about the behavior of electric motors, how they are connected to reduction gearboxes, and their overall system performance [7]. This needs rigorous analysis and measurement including but not limited to vibration analysis, noise measurement, and system dynamics modeling. These tools are vital for engineers to correctly pinpoint and troubleshoot NVH problems, ensuring better performance and passenger comfort during driving.

However, the EV industry faces further complexities with the price volatility and uncertain supply of rare earth materials, making PMSMs less attractive for mass production. Companies are exploring alternative technologies like SRMs for cost efficiency. SRMs, however, exhibit worse vibro-acoustic behavior than PMSMs due to their non-sinusoidal waveforms and high harmonic content. These harmonics, proportional to speed, can cause stator vibration, with high rotational speeds making low-order harmonics resonate structurally sooner [8,9].

Based on the authors' experiences, vehicle OEMs often depend on component suppliers for designing, testing, and manufacturing sub-systems. Suppliers strive to create "quiet" sub-systems, but the assembled electric powertrain might still be unacceptably noisy. Addressing these issues effectively involves the use of Computer-Aided Engineering (CAE) tools for simulation and modeling. The challenge lies in the application of these tools, their functionality, and the timing of their deployment in the development cycle.

The transition to EVs brings unique NVH challenges, underscoring the need for effective modeling and analysis [10]. The absence of ICE noise in EVs alters the NVH landscape significantly, making other noise sources more noticeable and requiring a focus on psychoacoustics. Furthermore, the various weight distributions in EVs result in new excitation frequencies and responses. For the design and development of EVs, a systematic NVH analysis is necessary to achieve best-in-class acoustic comfort and performance considering complex noise generation and propagation characteristics in EV powertrains, requiring multi-disciplinary know-how to efficiently deal with these challenges [11].

In contrast to earlier studies that typically concentrate on specific components, our methodology examines the entire drivetrain system through a comprehensive, system-wide approach. This involves utilizing holistic strategies in simulations to understand the complex interactions and dynamic behaviors of the complete drivetrain system. We believe this paper will be an invaluable resource for engineers and researchers aiming to enhance the NVH (noise, vibration, and harshness) characteristics of electric vehicles. It sheds light on the latest research developments and possible future innovations in this swiftly advancing field.

This advanced review not only facilitates a deeper understanding of NVH challenges in electric drivetrains but also offers practical tools and methods for engineers to design quieter and more comfortable electric vehicles. The originality of this work is found in its thorough analysis and integration of various NVH sources and solutions, along with presenting the most recent research outcomes and technological advancements in this domain. The following sections outline the contents of this manuscript in detail:

- Section 2: Key Contributors to NVH in EV Powertrains: This section explores the primary sources of NVH in EV powertrains, including the electric motor, power inverter, and transmission. It examines how these components contribute to the overall NVH profile and the challenges they pose when integrated into a complete system.
- Section 3: Noise Reduction Methods: Various methods for mitigating NVH in EV powertrains are discussed here. The section covers strategies for reducing mechanical noise, electromagnetic noise from electric motors and inverters, and aerodynamic and fluid flow noise, emphasizing advanced design techniques and material selection.
- Section 4: Development of Simulation Models for NVH Analysis: This section focuses on the development of computational models for NVH analysis. It details the methodologies and tools used, such as multi-body dynamics (MBD), the finite

element method (FEM), and the boundary element method (BEM), and the integration of these models to analyze the dynamic behavior and acoustic characteristics of the powertrain.

◦ Section 5: Acoustic Analysis Setup and Results: The setup and results of acoustic simulations are presented in this section. It includes details on microphone placement, modeling of acoustic sources, and the interpretation of simulation results, providing insights into the acoustic behavior of the powertrain and guiding noise control solutions.
◦ Section 6: Conclusions: The manuscript concludes with a summary of the findings and their implications for NVH management in EV powertrains. It underscores the necessity of a holistic system-level approach and the application of advanced simulation techniques to effectively address NVH challenges in electric vehicles.

2. Key Contributors to NVH in EV Powertrains

In EV powertrains, the main sources for NVH are the electric motor, the power inverter, and the transmission with a gear reducer [12] and, if present, the cooling fan and pumps, as seen in Figure 1. All of the individual parts have acceptable NVH on their own, but challenges arise when they operate in conjunction.

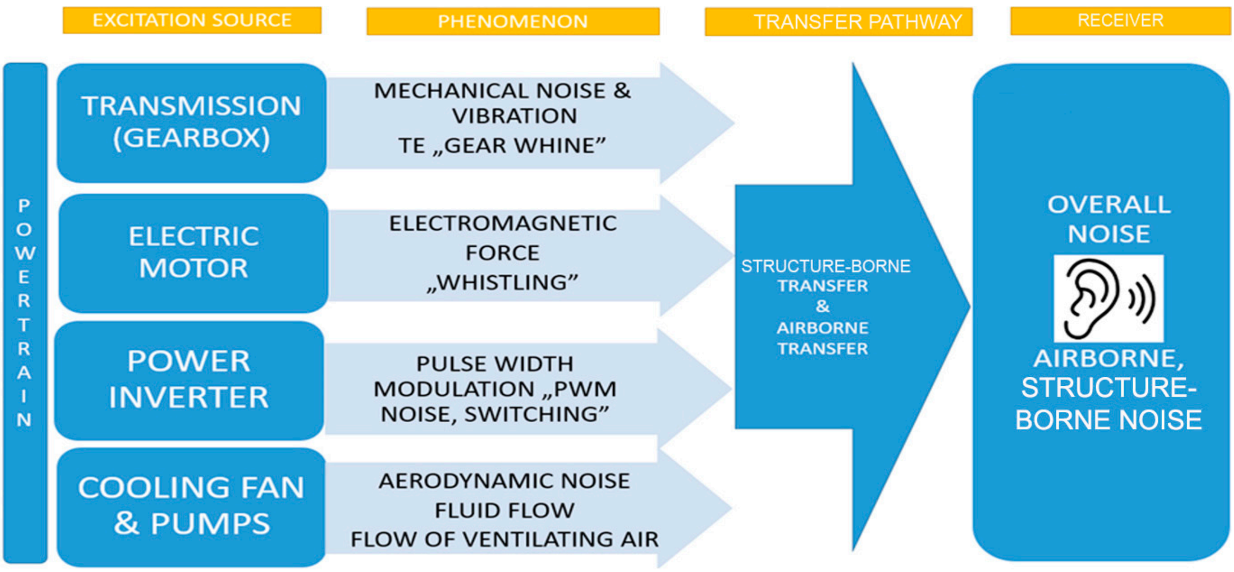

Figure 1. EV powertrain radiated noise generation mechanism.

- Transmission and gear reducer (gearbox): mechanical ooise (commonly known as 'gear whine'): this occurs due to vibrations caused by gear transmission error (TE), excitable mechanically [13].
- Electric Motor: generates excitations via electromagnetic forces, causing what is commonly known as "whistling" or slot/pole noise (also referred to as 'slotting').
- Power Inverter and Electronics: include components that contain higher-order harmonics, leading to pulse width modulation (PWM noise), ('switching').
- Cooling Fan and Pumps: Produce aerodynamic noise and fluid flow noise.

The combination of these four elements accounts for most of the overall noise in EVs, which includes both airborne and structural noise. Understanding these contributors is crucial.

Noise and vibration sources, for example, the electric motor, gearbox, and power electronics, act as excitation sources. These sources generate vibrations and noise, which are transmitted through various pathways. Structural vibrations travel through the vehicle's structure, termed structural-borne noise, while airborne noise moves through the air. The structural vibration pathways and radiated noise play a crucial role in how these sounds and vibrations are perceived. Ultimately, these noises and vibrations are received by the human ear, termed the 'Ear Receiver', impacting the overall sensory experience and comfort inside the vehicle, as seen in Figure 2. Addressing both the excitation sources and the transfer pathways is essential for minimizing NV impacts on vehicle integrity and occupant comfort [14].

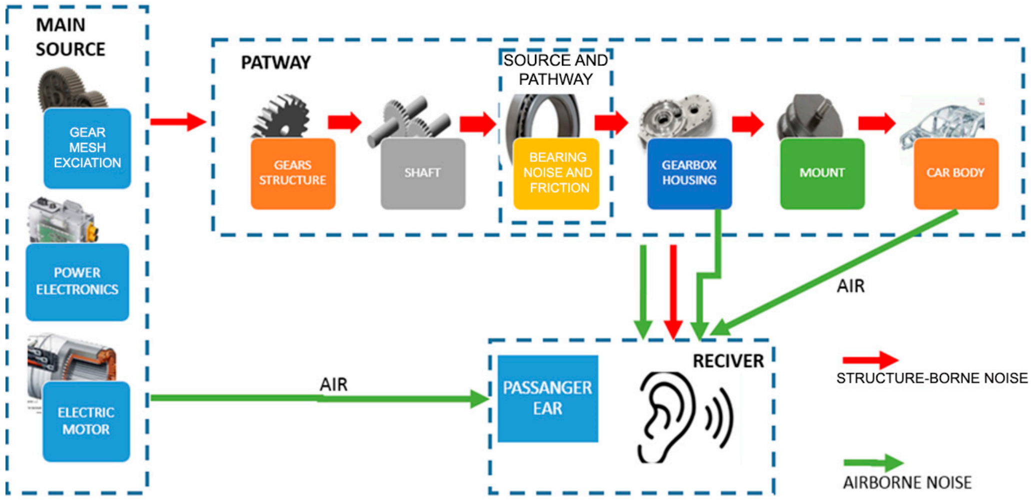

Figure 2. Noise generation mechanism and transmission path in electromechanical powertrain.

2.1. Contributors to Mechanical Noise

Factors influencing mechanical noise and vibration in EV powertrains are comprehensive. They include gear dynamics, notably TE, which leads to gear whine. TE is influenced by various factors, such as gear macro- and micro-geometry, changes in gear stiffness, assembly misalignments, and manufacturing errors [15]. These aspects of TE contribute to vibrations that pass through shafts and bearings into the casing, exacerbating structural resonances. Alongside TE, bearing noise, shaft imbalances, misalignments, eccentricity, sliding contact interactions, and tightening faults all contribute to the NVH profile. Addressing these, including understanding the precise causes and transmission pathways of TE-induced vibrations, is crucial for reducing mechanical noise and enhancing the overall NVH performance of EVs.

2.2. Noise from Electric Motors

Electromagnetic noise in EV powertrains, a significant factor in vehicle NVH characteristics, is notably influenced by interactions within the electric motor, specifically in the PMSM. The electromagnetic forces in the air gap between the stator and rotor can lead to a phenomenon known as whistling. These forces result in radial, axial, and tangential components, causing various vibrations in the stator and rotor [16]. Radial force harmonics primarily generate stator vibrations, while tangential forces can induce torsional vibrations in both the stator and rotor, presenting high NVH risks. Oscillations in these frequencies from the stator to the housing can amplify structural vibrations and thus cause beeping. These vibrational interactions, though complex and difficult to understand, are the essential mechanisms for the generation of electromagnetic noise in EV drive chain elements. Fortunately, they can be controlled to some extent [17].

2.3. Noise from Inverters

The inverter, in addition to the electronics, is one of the sources of electromagnetic noise. This is especially due to PWM noise, which is typically called "switching" noise. This is because the inverter plays a role in converting a direct current to an alternating current for electric motors using a PWM strategy that involves rapid switching. This process generates higher-order harmonics, affecting electromagnetic forces, and contains

NVH hazards [18]. A significant design challenge for power inverters is balancing the reduction in these harmonic excitations, which can limit maximum efficiency, as the effort to minimize NVH effects on the motor, possibly within the transmission, can affect overall efficiency. This requires a thorough examination of the design of the NVH as well as the power inverter to optimize the trade-offs between them.

2.4. Contributors to Aerodynamic Noises and Fluid Flow

Aerodynamic noise and fluid flow are major contributors to NVH characteristics in EV powertrains. The cooling fan contributes the majority of aerodynamic noise generated in the engine compartment, depending on whether the motor is sealed or not. Primary noise is created by vent holes in non-sealed motors and external fans in sealed motors. This noise category includes broadband and tonal noise, especially at the blade passing frequency (BPF) and its harmonics [19]. Additionally, fluid flow noise, especially from water pumps used for cooling purposes, adds to the overall NVH profile. These pumps can generate noise during operation, further influencing the acoustic environment of the vehicle.

2.5. Factors Influencing Noise from Electromagnetic Components

- Mechanical Deformations and Vibrations: These arise from various factors including the slot design, winding distributions, current waveform distortions, air gap variations, rotor eccentricity, and phase imbalances. These contribute to mechanical deformations and vibrations through complex harmonic forces and torques [20].
- Stator-Frame Resonance: The stator frame structure acts as the primary noise radiator of the machine. Resonance can occur when the radial force frequency aligns with the stator frame's natural frequencies, leading to significant noise [21].
- Magnetostrictive Noise: This is due to the periodic elongation or contraction of the core material, which, in high-power applications like in EVs and HEVs, can contribute substantially to the overall noise [21].
- Parasitic Oscillation Torque: In inverter-fed motors, parasitic oscillating torques arise from time harmonics in the stator currents and can be exacerbated by voltage ripples from the rectifier [21].

3. Noise Reduction Methods

During the development of EVs, it is in the interest of the manufacturers to meet acoustic regulations and the customers' needs. All kinds of noise reduction measures must be applied to all components of the drive chain. With advanced design techniques, as well as large-scale precision engineering and poroelastic noise insulation materials, noise and vibration from EV drivetrains can be greatly reduced. Special methods of avoiding mechanical noise, electrical motor noise, electromagnetic interference emitted by inverters, and aerodynamic and possibly fluid flow noise are presented in detail in the subsections.

3.1. Preventing Mechanical Noise

Preventing mechanical noise in various applications, particularly in industries like automotive, manufacturing, and construction, involves a comprehensive set of strategies aimed at reducing or eliminating noise sources. These methods encompass material selection, design optimization, isolation of noise sources, precision engineering, damping techniques, controlling operational parameters, and specialized gear and bearing design [22].

For EV powertrains, noise reduction involves balancing the rotor to minimize dynamic vibration and noise emission. The noise of rolling bearings is controlled by the requirements of strict mechanical work, perfect lubrication, and no foreign bodies. Additionally, sleeve bearings generally exhibit lower mechanical noise levels, but these noise levels depend on factors like surface roughness and lubrication quality [23]. Proper tuning of these factors can greatly reduce the high-frequency mechanical noise and vibration of EV powertrains.

Mounting accessory components into the body of EVs poses unique challenges. Controlling bracket and component resonances and ensuring they are isolated properly is key to maintaining performance levels similar to traditional vehicles as we enter the EV era.

- Selection and Environmental Dependence on Material: The use of materials with natural damping properties is important to help control mechanical noise. For example, vibrations may be absorbed, and the transmission of noise would be reduced when using rubber or Polyurethane (PU) mounts or pads. Foams and composites also work well in areas where lots of noise is absorbed [23].
- Optimization of Design: Designing components and systems with minimal noise production will reduce mechanical noise. Tightening and designing assemblies to not rattle (meaning they no longer vibrate or create noise) is crucial. Design techniques, such as finite element analysis (FEA), are particularly useful in detecting and addressing possible noise problems [24].
- Noise Source Isolation: It should be ensured that machinery or other noise-generating components are isolated from the rest of the structure. This is possible when sound transmission is prevented, such as through isolation mounts, enclosures, or barriers. Isolating sensitive components from vibration sources is particularly important [25].
- Precision Engineering and Manufacturing: A high level of precision provided in engineering and manufacturing processes equals lower mechanical noise. This is achieved by keeping tolerances tight, ensuring proper alignment, and balancing moving parts. Regular checks are necessary to prevent noise development caused by excessive wear [26].
- Application of Damping Techniques: It may be easier to reduce noise from a vibration source than to reduce the vibration itself. Selective damping of the machinery or structure may be considered. This could include damping coatings or layers in mechanical systems and actively or passively moving tuned mass dampers that absorb certain vibration frequencies [27].
- Adjusting Operational Parameters: Adjusting parameters like speed, torque, and load can help reduce mechanical operation noise. Running machines at speeds that do not hit resonances is a great idea, as is stepping into and out of new operations smoothly [28].
- Active Noise Control (ANC): ANC reduces noise by using electronic means. It uses microphones to listen to the sound and speakers to create a counter-noise that effectively cancels the original noise, especially where conventional noise reduction methods are unsuitable [29].
- Tailored Gear and Bearing Design: Gear design profoundly affects NVH risks in mechanical systems. Eliminating stiffness variation and optimizing the contact ratio can be achieved through the modification of macro- and micro-geometry of gears to minimize gear TE. Noise can be reduced through strategies such as raising the helix angle of gear sets, though this may also increase the axial loads placed on bearings and reduce efficiency. Similarly, an augmented contact ratio due to an inclined tooth addendum can increase frictional losses [30]. Key among these design considerations are reducing NVH while preserving efficiency and handling bearing loads.

3.2. Preventing Electric Motor Noise

Suppressing the electromagnetic noise in electric motors reflects directly on improving the overall system performance of EV powertrains. This type of noise is mainly produced by electromagnetic forces due to motor operation. Addressing this issue requires a variety of measures to counteract the forces impacting both large-scale and fine design elements.

Design Modification Parameters and Techniques: Various design parameters such as pole combinations or magnet shapes induce electromotive forces. Fine-tuning these settings helps create a more even force distribution, as too much force can lead to possible noise generation. For example, torque ripple or radial force harmonics, and their resulting electromagnetic noise, can be mitigated by methods such as rotor skewing. However, a larger skew angle can decrease back electromotive force (EMF), affecting motor performance. It is essential to balance noise reduction with motor efficiency and output in this case, requiring sophisticated tuning [31].

System Resonance and Asymmetry Reduction: Resonance—a condition that can add noise while tightening vibrations—between magnetic forces and structural modes of the motor should be avoided [32]. Simulations can help recognize and mitigate resonant frequencies at the design stage. Alignment of the center of mass with the center of rotation, positioning the magnets at their ideal locations, achieving uniform magnetization of the motor magnets, and ensuring adequate roundness of laminations can reduce these asymmetries [33] to prevent irregularities in the magnetic field.

Magnetic-Specific Noise Mitigation Strategies: To further diminish magnetic noise and vibrations, altering the motor's magnetic properties can be highly effective. Strategies include the following [34]:

- Pole Shaping: Refining the shape of magnetic poles to optimize the magnetic field distribution.
- Modulation of Pole and Slot Width/Position: Adjusting poles and slots can influence the magnetic field's harmonics and, consequently, the noise and vibrations produced.
- Notches and Flux Barriers: Introducing notches or flux barriers to disrupt magnetic flux paths and control flux flow.
- Airgap Increase: Expanding the airgap between the rotor and stator to lower magnetic forces, while carefully considering the potential effects on motor efficiency and torque.

3.3. Preventing Electromagnetic Noise in Power Inverter:

- High-Frequency Adjustment: By increasing the inverter's switching frequency above the audible range, the noise becomes imperceptible to the human ear.
- Control Strategies: These highlight the role of control strategies in balancing vibroacoustic and electrical performances, especially in induction and synchronous machines, to optimize for either efficiency or noise reduction [35].
- Vibration Isolation: Integrating the inverter into the motor's isolation system can diminish the vibration transmitted from the inverter [36].
- Acoustic Shielding: Wrapping the inverter in absorptive or barrier layers can obstruct the airborne noise transfer path, thereby reducing the noise that reaches the cabin [37,38].

3.4. Preventing Aerodynamic and Fluid Flow Noise

- Water Pump Noise: Focusing on strategic mounting and location is crucial to prevent aerodynamic and fluid flow noise in powertrains, especially from water pumps in HEVs/EVs. Additionally, minimizing pulsation transmission through organized fluid conductor layouts, stiffening large flat metal areas, and selecting pumps with low noise ratings are key strategies. These approaches address the root causes of noise and offer practical solutions for engineers designing quieter and more efficient vehicle systems [19].
- Cooling Fan Noise: Utilized for vehicle cooling or dedicated HEV component cooling, these fans' noise should be masked by other sources. Controlling noise levels at low speeds and in idle conditions is vital [19].

4. Development of Simulation Models for NVH Analysis

The powertrains of EVs are very complex energy chains for the simulation of radiated noise and require many different methodologies and tools. The typical powertrain in an EV consists of an electric motor combined with a reduction gear. To accurately predict the noise generated by the overall powertrain, it is necessary to consider the dynamic performance and acoustic characteristics of both the electric motor and gear reduction mechanism as a whole. How those two main components—the electric motor and the gear reducer—are integrated with each other has a major influence on the noise and vibration character of the EV powertrain [39].

Developing a computational model of the powertrain often uses Finite-Difference Time-Domain (FDTD), multi-body dynamics (MBD), the finite element method (FEM), and the boundary element method (BEM) for structural analysis and noise prediction. This model is crucial for simulating the behavior of the powertrain under various conditions and for predicting radiated noise (Figure 3) [40].

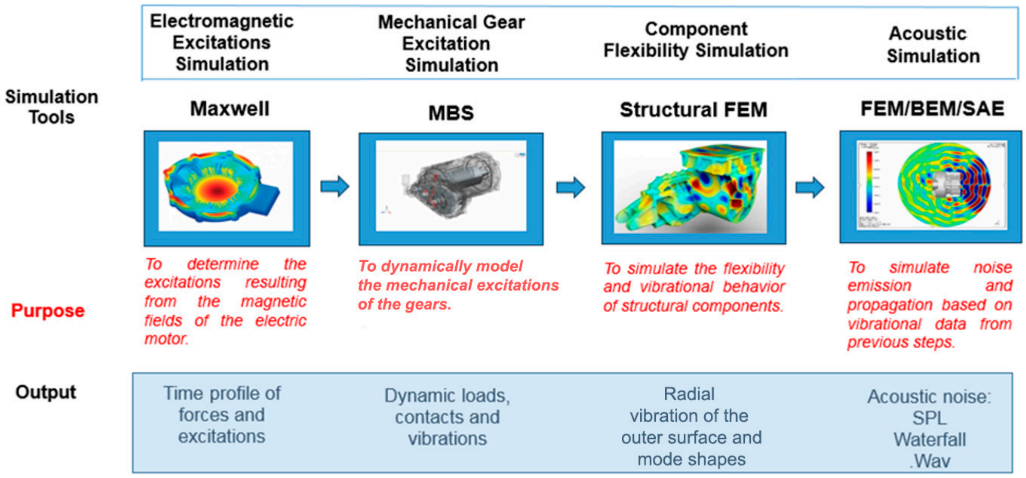

Figure 3. Recommended numerical multiphysics simulation workflow—overall simulation process.

4.1. EM Simulation

This type of excitation is generated by electromagnetic forces, and in electric motors, it is the main source that contributes to NVH problems. Such forces are usually estimated through analytical or numerical calculations, with the latter often involving software tools to numerically solve differential equations describing the electrical machine. These equations consider the geometry and electromagnetic nonlinearities of the machine. The vibration response due to these forces is then analyzed using 3D structural FEA or MBD [5].

In a study by Duda et al. (2021), the integration of electromagnetic finite element models into a multi-body simulation environment showed that specific eigenmodes of the generator structure, such as hexagon- and pentagon-shaped modes, are excited at particular rotational speeds. These eigenmodes, when excited, can significantly contribute to the acoustic emissions of the turbine. For example, during a ramp-up test, the hexagon-shaped eigenmode was excited at a rotational speed of 11 rpm, leading to increased vibrations that contribute to the overall noise profile [41].

State-of-the-art vibro-acoustic simulation of an electrical machine involves coupling a co-simulation, typically between a tool performing electromagnetism analysis like ANSYS Maxwell 2024 R2 [42], JMAG Ver.22.2 [43], or Siemens MagNet 2021.1 [44], and an FE-based solver that defines structural behavior. This necessitates that the structural FEA be solved at each time step.

One of the leaders in electromagnetic field simulation software, ANSYS Maxwell, is used to design and analyze 3D/2D electric motors, actuators, sensors, transformers, and other electromechanical devices. The goal is to simulate electromagnetic fields and how much force is generated by magnetic fields, resulting in vibrations in electric motors. The software accurately captures the detailed electromagnetic interactions that occur in a motor, taking into account the stator, rotor, windings, and magnetic materials.

Combining these results with the data from Maxwell electromagnetic simulation tools with MBD and FEA software is crucial for understanding how electromagnetic forces affect NVH in the powertrain overall. For example, data from Maxwell are imported into MBD tools such as RecurDyn 2023 [45] or Adams 2024.1 [46], or FEA tools such as ANSYS Mechanical 2024 R2 [47] or Nastran 2024.1 [48], to analyze vibration and noise tendencies caused by the forces in the motor and its surroundings.

Maxwell allows engineers to predict and visualize the magnitude and distribution of electromagnetic forces in the motor [49]. If these forces are unequal or interact with mechanical resonances, significant vibrations can occur [50]. The vibration data generated from the electromagnetic analysis are then used in acoustic simulations to understand how these vibrations manifest as audible noise, contributing to the vehicle's NVH profile.

In addition, electromagnetic simulation tools like Maxwell are used to ensure excellent performance in the design optimization step. Based on changes in the electromagnetic component geometry, winding configuration, and material property modifications, design engineers can reduce unwanted vibrational behavior and improve the NVH performance of electric motors. In a study by Levent et al. (2020), the optimization of magnet size and position in PMSMs resulted in a significant reduction in torque ripple from 46.6% to 16%. This highlights the importance of precise electromagnetic modeling and the effectiveness of advanced optimization techniques in reducing vibratory behavior and improving overall motor performance [51].

4.2. Multi-Body Dynamic Simulation Using Flexible Bodies

At the beginning of a multi-body dynamic simulation, the electric motor is a critical component of the powertrain and is included in the system model to describe all of its complex dynamics. This simulation also extends to address the impact of the electric motor on all other powertrain parts, such as gears and shafts, covering rotational dynamics, torque generation, and any flexibilities in motor mounts or couplings. The simulation stretches beyond regular rigid body dynamics and incorporates the flexibility of bodies, emulating the actual dynamic behavior of motors. The interactions among the dynamic loads, vibrations of the gears, and contact forces are precisely represented by a corresponding mechanical model (Figure 4) [52].

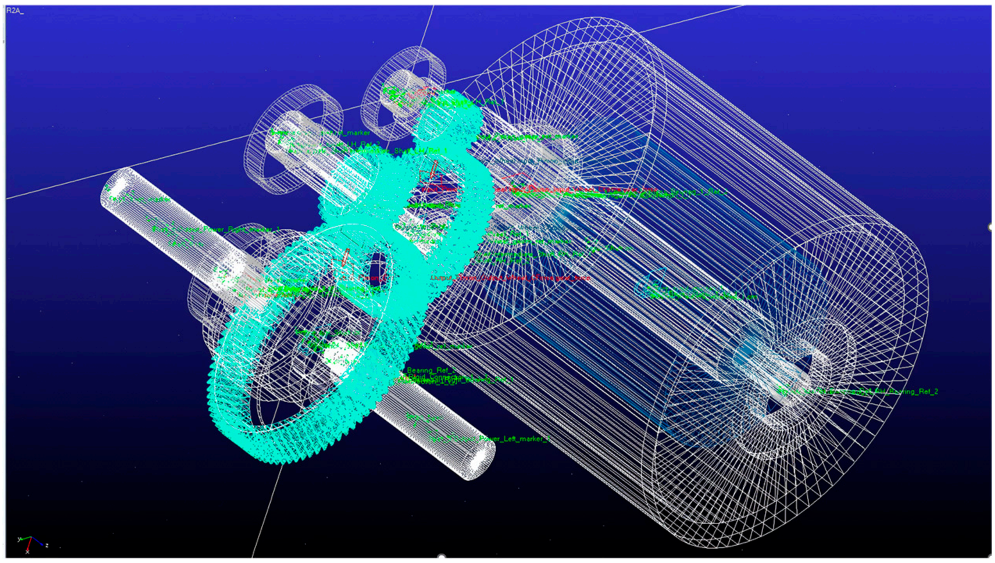

Figure 4. Multi-body dynamics (MBD) simulation of an electric drive system using Adams.

4.3. Structural Analysis

In the structural analysis phase, the focus is on loads and stresses specific to the electric motor, including electromagnetic forces, mechanical stresses from torque generation, and vibrational forces. Using finite element methods, the structural integrity of the motor and its impact on the overall powertrain structure, such as the casing or mounting points, is analyzed. This step is crucial for understanding how vibrations originate from the motor and propagate through the powertrain. In a study by Pellerey et al. (2012), it was demonstrated that specific harmonics of the supply currents can significantly influence the vibratory behavior of electric machines. For example, a harmonic supply resulted in an average increase of 17.3 dB in the radial acceleration of the stator surface compared to a sinusoidal supply. This underscores the importance of accurate acoustic modeling and the effectiveness of advanced noise control strategies in mitigating the effects of supply harmonics [53].

4.4. Acoustic Radiation Calculations

This concern is addressed by the acoustic model representing the transformation of these vibrations into sounds (Figure 5). The focus is the vibrations from the motor, particularly those stemming from electromagnetic forces and gear interactions within the motor assembly, which contribute to the overall noise of the powertrain [54,55].

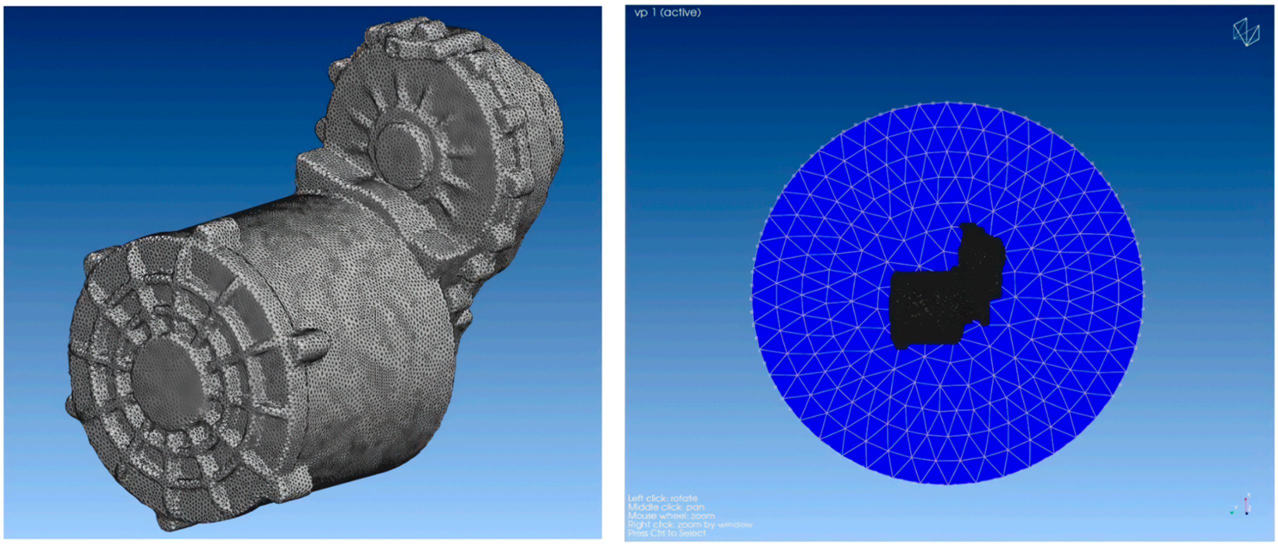

Figure 5. Meshing and acoustic field simulation of an electric motor performed in Actran. The **left** image shows the meshing of the electric motor for detailed vibro-acoustic simulation, while the **right** image illustrates the acoustic field around the motor.

In a study by Kim and Altinsoy, active road noise control systems achieved an average noise attenuation of 3.4 dB at the driver and rear right-hand side seat positions for frequencies up to 400 Hz. This underscores the importance of accurate acoustic modeling and the effectiveness of advanced noise control strategies [39].

4.5. Common Workflow in Fully Numerical CAE Software

The authors suggest that the following workflow represents a typical process for NVH analysis and simulation in EV powertrain development. They emphasize that the specific steps and tools used may vary depending on the specific project:

1. Defining Objectives and Requirements: Establish goals of the simulation, focusing on NVH aspects like noise source identification, noise level evaluation, and noise reduction strategies. Define key parameters and performance indicators, including NVH-specific metrics.
2. Gathering and Preparing Data: Collect necessary data on the powertrain's physical properties, operational characteristics, and environmental factors from various sources.
3. Modeling the Powertrain Components (Incorporating MBD and Flexibility): Develop detailed models of powertrain components using FEM and integrate MBD modeling, including flexible components such as motor and gearbox housings, shafts, bearings, and gear tooth contacts.
4. Integrating Electromagnetic and Mechanical Models: Combine electromagnetic simulations with mechanical models for a comprehensive analysis of electromagnetic-induced vibrations.

5. Setting Up Acoustic Models: Develop acoustic models using methods like BEM for predicting sound wave generation from powertrain vibrations and defining the acoustic environment.
6. Validating Component Models: Independently validate each component model against experimental data for accuracy.
7. Assembling the Complete Powertrain Model: Integrate individual component models, ensuring accurate representation of interfaces and dynamic interactions.
8. Simulating Operational Conditions: Simulate various operational scenarios to understand the noise behavior under different EV conditions.
9. Analyzing NVH Simulation Results: Use Equivalent Radiated Power (ERP) to quantify the energy emitted as sound. Use Sound Pressure Level (SPL) to measure the acoustic energy perceived. Use Campbell diagrams (both 2D and 3D) to visualize the frequency response and identify critical speeds. Evaluate individual modes in both time and frequency domains for detailed analysis. Obtain results for casing, including stress, displacement, and insights for optimization.
10. Refining the Model: Based on NVH analysis, refine the model for accuracy, adjusting material properties, boundary conditions, or geometry.
11. Iterative Testing and Optimization: Iterate the simulation process, adjusting the model based on NVH findings and retesting for noise reduction or design improvements. Final validation and reporting: validate the final model against known data or experimental results.
12. NVH Result Interpretation and Application: Interpret NVH results such as ERP, SPL, and Campbell diagrams to understand the acoustic behavior of the powertrain. Use time domain and frequency domain analyses to identify and evaluate specific vibration modes and their impact on noise and harshness. Analyze casing stress and displacement results to inform structural optimization for reducing noise and improving durability.
13. Design Recommendations Based on NVH Analysis: Based on the comprehensive NVH analysis, make design recommendations aimed at reducing noise and vibration, while enhancing the overall sound quality of the powertrain. Propose modifications to the powertrain design.

During these steps, it is useful to collaborate with experts in electromagnetics, acoustics, and mechanical engineering to ensure the model is accurate and relevant to real-world powertrain noise scenarios while optimizing EV combinations. The holistic approach applied to NVH analysis and simulation in EV powertrain development is essential for effective noise reduction and ultimately improving acoustic quality. This comprehensive approach combines detailed modeling of powertrain components, flexible elements, and state-of-the-art acoustic methods. A fundamental part of this process is simulating the electric motor, which is essential because of the electromagnetic forces it creates that can cause vibrations and account for a large part of overall NVH. By using electromagnetic field simulation software tools like ANSYS Maxwell, engineers can forecast motor vibration properties that are required for a comprehensive NVH analysis.

The smooth interfacing of multiple software modules is critical for the success of this approach. Optimal results are often achieved in a software environment or family of compatible software that allows for multiphysics simulations to be implemented [56]. These simulations play a crucial role in the exact description of the highly integrated coupling system of EV powertrains. This extends to the detailed component modeling of electric motor and gearbox housings, and flexible shafts, as well as the geometries of rolling bearings, bearing forces, 3D gear tooth contact, and micro-geometries. It involves examining each automotive component that contributes to noise and vibration in the vehicle.

The NVH analysis workflow in EV powertrain development encompasses multiple phases, such as flexible component modeling in multi-body dynamics (MBD), structural analysis, and acoustic radiation calculations. This simulation can predict the NVH attributes of the powertrain by representing these detailed features [57]. This, in return, enables the development of better mitigation strategies, taking into account the entire noise and vibration picture in powertrain design and optimization. This is achieved by a detailed multiphysics investigation, which helps in the understanding the NVH behavior more accurately and supports sound engine concept development to streamline noise and vibration reduction in EV powertrains.

5. Acoustic Analysis Setup and Results

- Microphone Placement: The process begins with placing virtual microphones around the powertrain model. Positioning is crucial to correctly capture sound emanating from different parts of the system. This involves considering factors like the distance to the noise source, the recording location on the car, and the directionality of the microphones [58,59] (Figure 6).

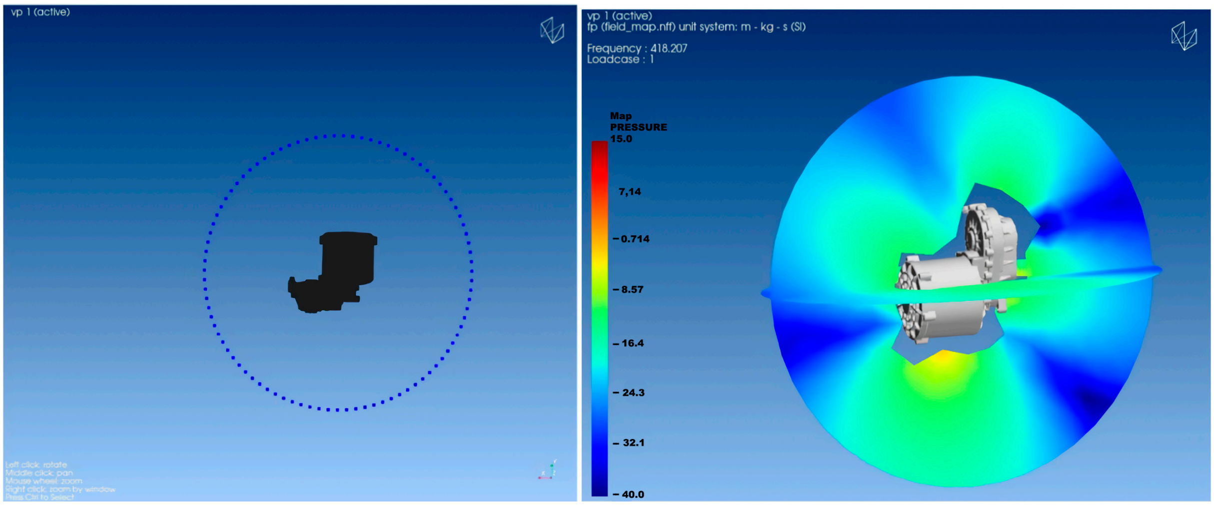

Figure 6. Microphone placement and environmental noise level at 418 Hz frequency. The **left** image shows the positioning of the microphone relative to the electric motor, while the **right** image displays the resulting acoustic pressure field.

- Simulation Environment: Acoustic analysis is conducted in a simulated environment that accurately reflects real-world conditions. This includes specifying the acoustic properties of the environment, such as air density and temperature, which affect sound propagation [60].
- Modeling Acoustic Sources: The powertrain components are modeled as sound sources. This requires understanding which components are most likely to generate noise, at what frequencies, and under what operating conditions [61].

Interpretation of Acoustic Results

- Radiation Patterns: Understanding the acoustic radiation patterns of the powertrain can reveal how sound waves emanate from the noise source. These patterns fluctuate continuously, and by graphically representing them, engineers can precisely locate areas of high noise emission [62]. This knowledge is essential for designing countermeasures to contain or deflect the sound away from sensitive areas, such as the passenger cabin.
- Sound Pressure Levels (SPLs): SPL measurements provide quantitative data on the loudness of noise at various locations around the powertrain. Areas with the highest SPL readings are of particular concern as they directly impact the comfort of the vehicle's occupants [63]. SPL data also ensure that the vehicle meets legal noise regulations and industry standards for both interior and exterior noise levels.
- Frequency Analysis: Identifying the principal and problematic frequencies is crucial for recognizing entrenched NVH issues. Some frequencies may be more perceptible

and annoying to the human ear, making them prime targets for reduction strategies. Frequency analysis facilitates the development of noise control solutions, such as damping materials or active noise control systems, tailored to suppress specific frequencies [64].

- Equivalent Radiated Power: This metric quantifies the total sound power produced by the powertrain. It is important to assess the overall noise contribution of the powertrain and evaluate the relative impact of different noise reduction strategies [65]. Figure 7 illustrates the variation in radiated acoustic power across different frequencies, highlighting significant peaks.

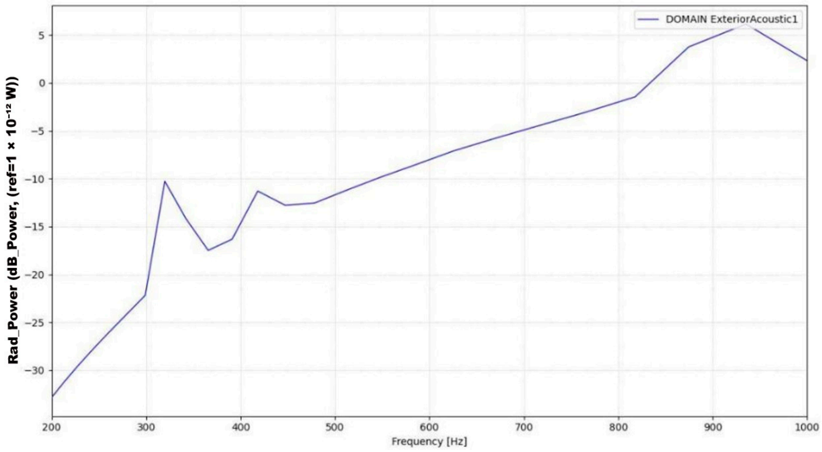

Figure 7. Frequency response of the acoustic power radiated by the electric motor.

- Campbell Diagrams: These 2D and 3D diagrams are commonly used to graphically represent the powertrain's frequency response [66]. They help identify critical speeds where noise and vibration significantly increase, making them important tools for diagnosing and mitigating resonance issues [67].

6. Conclusions

To conclude, this study presents an extensive review of noise, vibration, and harshness (NVH) management strategies in electric vehicle (EV) powertrains. The swift rise in EV adoption introduces distinct NVH challenges due to the lack of internal combustion engine (ICE) noise, which makes drivetrain noise more noticeable. Our research identifies several major contributors to NVH in EV powertrains, such as electric motors, inverters, and gear systems, and assesses the effectiveness of various noise mitigation methods.

Our approach stands out for its holistic, system-level perspective, contrasting with previous studies that often concentrate on individual components. We highlight the importance of integrating simulation and modeling techniques, including multi-body dynamics (MBD) and the finite element method (FEM), to analyze the entire drivetrain system. This comprehensive method allows for a deeper understanding of the complex interactions and dynamic behaviors within the complete drivetrain system, providing fresh insights into NVH management.

Moreover, our study fills a gap in the current literature by offering a general workflow for NVH simulations, which is often missing in other research. This workflow acts as a valuable guide for engineers and researchers, offering a structured approach to developing and analyzing models for NVH management in EV powertrains.

We also recognize the significance of visual data, such as graphs and charts, in reinforcing our findings. Although our main focus was on summarizing simulation experiences and methodologies, we are open to including specific examples and visualizations from our simulations to better illustrate the effectiveness of the methods presented.

The uniqueness of our work is showcased through the detailed analysis and integration of various NVH sources and solutions, alongside presenting the most recent research findings and technological advancements in this field. This thorough review not only enhances the understanding of NVH challenges in EV powertrains but also provides practical tools and methods for designing quieter and more comfortable electric vehicles.

Electric motor noise arises from electromagnetic forces, while inverters produce high-frequency noise due to pulse width modulation (PWM). NVH requirements are further complicated by mechanical issues such as gear failures and shaft imbalances, which increase unwanted frequencies.

Simulation and modeling techniques like multi-body dynamics (MBD), the finite element method (FEM), and multi-domain simulation are essential for predicting and addressing NVH issues. These techniques enable engineers to examine the entire powertrain system rather than individual components, ensuring comprehensive NVH management.

Our study emphasizes the importance of a holistic system-level approach to NVH and confirms the necessity of a detailed, all-encompassing analysis and measurement of electric motors, transmissions, and their interactions. This approach enhances both performance and comfort in EVs, even in the absence of the engine noise characteristic of ICE vehicles.

Simulation software such as ANSYS Maxwell for electromagnetic analysis and Adams for multi-body dynamics aids in accurately predicting and minimizing NVH issues, ensuring the powerful and efficient design of EV drivetrains.

In summary, addressing NVH in EVs requires holistic thinking and the integration of advanced simulation techniques with an understanding of the dynamic interactions within the powertrain. A system-wide approach is crucial for making EVs quieter, more comfortable, and more efficient.

7. Future Research Directions

Looking ahead, further research could explore the integration of advanced materials and innovative design techniques to further reduce NVH in EV powertrains. Additionally, the development of more sophisticated simulation models that can capture the interactions between various NVH sources in real time could significantly enhance predictive accuracy.

Emerging technologies, such as artificial intelligence and machine learning, offer promising avenues for optimizing NVH management strategies. These technologies could be used to analyze vast amounts of data from simulations and real-world tests to identify patterns and develop more effective noise reduction solutions.

Furthermore, expanding the scope of NVH research to include the impact of NVH on overall vehicle performance and passenger comfort, considering psychoacoustic factors, could provide a more comprehensive understanding of the NVH landscape in electric vehicles.

In conclusion, while significant progress has been made in understanding and managing NVH in EV powertrains, ongoing research and innovation are essential to keep pace with the rapid advancements in EV technology. By continuing to refine and expand our approaches, we can ensure the development of quieter, more efficient, and more comfortable electric vehicles in the future.

Author Contributions: Conceptualization: K.H.; methodology: K.H.; software: K.H.; validation: K.H.; formal analysis: K.H.; investigation: K.H.; resources: K.H.; data curation: K.H.; writing—original draft preparation: K.H.; writing—review and editing: K.H.; visualization: K.H.; supervision: A.Z.; project administration: K.H. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Wennmo, M. Helping Electric Vehicle Manufacturers Compete. *Gear Technology Magazine*. 29 September 2022. Available online: https://www.geartechnology.com/articles/30078-helping-electric-vehicle-manufacturers-compete (accessed on 12 January 2020).
2. EV-Volumes. *Global EV Sales for February 2022*; EV-Volumes: Trollhättan, Sweden; Available online: https://www.ev-volumes.com/ (accessed on 12 January 2020).
3. Virta. 1.06 Million New EVs Registered in Europe. Virta Global EV Charging Report. Available online: https://www.virta.global/ (accessed on 12 January 2020).
4. European Environment Agency. New Registrations of Electric Vehicles in Europe. Available online: https://www.eea.europa.eu/ (accessed on 2 February 2024).
5. Weber, J. Technological trends. In *Moving Times*; Springer: Wiesbaden, Germany, 2022; pp. 27–159. [CrossRef]
6. Kosuru, V.S.R.; Venkitaraman, A.K. Trends and challenges in electric vehicle motor drivelines—A review. *Int. J. Electr. Comput. Eng. Syst.* **2023**, *14*, 485–495. [CrossRef]
7. NAGASE. NVH Reduction in EVs. NAGASE Whitepaper. Available online: https://www.nagase.com/content/dam/nagase-www/en/resources/nvh-reduction/NAM%20NVH%20Reduction%20in%20EVs%20WP%200323.pdf (accessed on 1 March 2024).
8. Fuchs, A.; Nijman, E.; Priebsch, H.-H. (Eds.) *Automotive NVH Technology*, 1st ed.; Springer: Cham, Switzerland, 2015; Volume XVIII. [CrossRef]
9. James, B.M.; Hofmann, A. Simulating and reducing noise excited in an EV powertrain by a switched reluctance machine. In Proceedings of the 8th International Styrian Noise, Vibration & Harshness Congress: The European Automotive Noise Conference, Graz, Austria, 2–4 July 2014. [CrossRef]
10. Meek, B.; Van der Auwear, H.; De Langhe, K. Challenges in NVH for electric vehicles. In *Proceedings of the FISITA 2012 World Automotive Congress*; Lecture Notes in Electrical Engineering; Springer: Berlin/Heidelberg, Germany, 2013; Volume 191, pp. 56–72. [CrossRef]
11. Mehrgou, M.; Garcia de Madinabeitia, I.; Graf, B.; Zieher, F.; Priestner, C. *NVH Aspects of Electric Drives-Integration of Electric Machine, Gearbox, and Inverter*; SAE Technical Paper 2018-01-1556; SAE: Warrendale, PA, USA, 2018. [CrossRef]
12. Furness, M.; Craven, J. Silencing the Future—A System Level Approach to NVH. In Proceedings of the 32nd Electric Vehicle Symposium (EVS32), Lyon, France, 19–22 May 2019; Available online: https://mobex.io/webinar-library/silencing-the-future-dsds-approach-to-electrified-powertrain-nvh/ (accessed on 1 March 2024).
13. Magliacano, D.; Viscardi, M.; Ciminello, M.; Dimino, I.; Concilio, A. Feasibility study for a tonal vibration control system of a mounting bracket for automotive gearboxes. *Int. J. Mech.* **2016**, *10*, 403–410.
14. Le Besnerais, J.; Toubin, H.; Gning, P.; Devillers, E. *Electromagnetic Noise & Vibrations in Electrical Machines Webinar 7/8: Noise and Vibrations in Electrical Machines Application with MANATEE [Webinar Presentation]*; EOMYS Engineering: Lille, France, 2 June 2020.
15. Zhang, J.; Lv, C.; Li, Z. Investigation of high-speed dynamic transmission error testing using gear strain. *Machines* **2023**, *11*, 956. [CrossRef]
16. Fang, Y.; Zhang, T. Vibroacoustic characterization of a permanent magnet synchronous motor powertrain for electric vehicles. *IEEE Trans. Energy Convers.* **2018**, *33*, 272–280. [CrossRef]
17. Deng, C.; Deng, Q.; Liu, W.; Yu, C.; Hu, J.; Li, X. Analysis of vibration and noise for the powertrain system of electric vehicles under speed-varying operating conditions. *Math. Probl. Eng.* **2020**, *2020*, 6617291. [CrossRef]
18. Sarrazin, M.; Janssens, K.; Van der Auweraer, H. Influence of inverter PWM control schemes on noise signature of electric powertrains. In Proceedings of the 4th International Conference on Biomedical Ontology, Montreal, QC, Canada, 7–12 July 2013; pp. 2899–2906.
19. Cherng, J.G. Noise and vibration of cooling fan and accessory components. In *ME 570 Powertrain NVH of Electrified Vehicles*; Mechanical Engineering Department, University of Michigan-Dearborn: Dearborn, MI, USA, 2013; p. 48128.
20. Ermolaev, A.; Erofeev, V.; Plekhov, A.; Titov, D. Magnetic vibration in induction motor caused by supply voltage distortion. *Energies* **2022**, *15*, 9600. [CrossRef]
21. Li, J.; Yang, S.; Yang, J.; Li, F.; Zeng, Q.; Shao, J.; Chang, C.; Wu, N.; Chen, Y.; Li, K. Low-order radial modal test and analysis of drive motor stator. *Machines* **2021**, *9*, 97. [CrossRef]
22. Bučinskas, V.; Mirzaei, S.; Kirchner, K. Some aspects of bearing noise generation. *Solid State Phenom.* **2010**, *164*, 278–284. [CrossRef]
23. Hazra, S.; Reddy, K.J. A comparative study of properties of natural rubber and polyurethane-based powertrain mount on electric vehicle NVH performance. *Int. J. Veh. Noise Vib.* **2022**, *18*, 22–40. [CrossRef]
24. Kumar, D.; Kottalgi, S.; Sambharam, T.; Mandloi, P. A multiphysics optimization approach to design low noise and light weight electric powertrain noise, vibration and harshness (NVH) prediction of electric powertrain using finite element analysis (FEA) and optimization. In Proceedings of the IECON 2017—43rd Annual Conference of the IEEE Industrial Electronics Society, Beijing, China, 29 October–1 November 2017; pp. 1692–1697. [CrossRef]
25. Dylejko, P.; MacGillivray, I.; Moore, S.; Skvortsov, A. The Influence of Internal Resonances from Machinery Mounts on Radiated Noise from Ships. *IEEE J. Ocean. Eng.* **2017**, *42*, 399–409. [CrossRef]
26. Zhang, Z.; Yan, J.; Kuriyagawa, T. Manufacturing technologies toward extreme precision. *Int. J. Extrem. Manuf.* **2019**, *1*, 022001. [CrossRef]

27. Thelen, D.; Burkert, W. How to achieve lower tolerances in production balancing machines. In *Proceedings: Electrical Insulation Conference and Electrical Manufacturing and Coil Winding Technology Conference (Cat. No.03CH37480)*; IEEE: New York, NY, USA, 2003; pp. 339–342. [CrossRef]
28. Ayana, E.; Plahn, P.; Wejrzanowski, K.; Mohan, N. Active Torque Cancellation for transmitted vibration reduction of low cylinder count engines. In Proceedings of the 2009 IEEE Vehicle Power and Propulsion Conference, Dearborn, MI, USA, 7–10 September 2009; pp. 325–329. [CrossRef]
29. Schirmacher, R. Active noise control and active sound design—Enabling factors for new powertrain technologies. In Proceedings of the 6th International Styrian Noise, Vibration & Harshness Congress—Sustainable NVH Solutions Inspired by Ecology and Economy, Graz, Austria, 22–24 June 2022. [CrossRef]
30. Åkerblom, M. Gear Geometry for Reduced and Robust Transmission Error and Gearbox Noise, Report, Maskinkonstruktion; School of Industrial Engineering and Management. Machine Design, Trita-MMK. 2008. Available online: https://kth.diva-portal.org/smash/record.jsf?pid=diva2:139890&dswid=281 (accessed on 12 March 2024).
31. Hosseini, S.; Alinejad-Beromi, Y. Noise reduction in switched reluctance motor by modifying the structures. *IET Electr. Power Appl.* **2021**, *14*, 2863–2872. [CrossRef]
32. Humbert, L.; Pellerey, P.; Cristaudo, S. Electromagnetic and structural coupled simulation to investigate NVH behavior of an electrical automotive powertrain. *SAE Int. J. Altern. Powertrains* **2012**, *1*, 395–404. [CrossRef]
33. Liu, G.; Gao, A.; Chen, Q.; Mao, Y.; Xu, G. Vibration and noise optimization of new asymmetric modular PMaSynRM. *Chin. J. Electr. Eng.* **2023**, *9*, 57–70. [CrossRef]
34. Pyrhönen, J.; Jokinen, T.; Hrabovcová, V. *Design of Rotating Electrical Machines*, 1st ed.; John Wiley & Sons, Ltd.: Hoboken, NJ, USA, 2014; pp. 167–491. [CrossRef]
35. Subramaniam, U.; Bhaskar, S.M.; Almakhles, D.J.; Padmanaban, S.; Leonowicz, Z. Investigations on EMI mitigation techniques: Intent to reduce grid-tied PV inverter common mode current and voltage. *Energies* **2019**, *12*, 3395. [CrossRef]
36. Henderson, J.; Plummer, A.; Johnston, N. An electro-hydrostatic actuator for hybrid active-passive vibration isolation. *Int. J. Hydromechatronics* **2018**, *1*, 47–71. [CrossRef]
37. Salmani, H.; Khalkhali, A.; Mohsenifar, A. A practical procedure for vehicle sound package design using statistical energy analysis. *Proc. Inst. Mech. Eng. Part D J. Automob. Eng.* **2022**, *237*, 3054–3069. [CrossRef]
38. Law, H.; Law, J.; Kierzkowski, M. Absorptive noise barrier development. *J. Acoust. Soc. Am.* **2023**, *154*, A351. [CrossRef]
39. Kim, S.; Altinsoy, M.E. Active control of road noise considering the vibro-acoustic transfer path of a passenger car. *Appl. Acoust.* **2022**, *192*, 108741. [CrossRef]
40. Horváth, K.; Ambrus, Z. Vibro-acoustic simulation of gearboxes—A literature review. In Proceedings of the 26th International Ph.D. Conference (PEME XXVI), Debrecen, Hungary, 9–10 November 2023; Professzorok az Európai Magyarországért: Budapest, Hungary; Miskolc, Hungary, 2023; pp. 73–81.
41. Duda, T.; Mülder, C.; Jacobs, G.; Hameyer, K.; Bosse, D.; Cardaun, M. Integration of electromagnetic finite element models in a multibody simulation to evaluate vibrations in direct-drive generators. *Originalarbeiten/Originals* **2021**, *85*, 257–264. [CrossRef]
42. Ansys, Inc. Ansys Maxwell. Available online: https://www.ansys.com/products/electronics/ansys-maxwell (accessed on 16 February 2024).
43. JSOL Corporation. JMAG: Simulation Technology for Electromechanical Design. Available online: https://www.jmag-international.com/ (accessed on 3 February 2024).
44. Siemens Digital Industries Software. Simcenter MAGNET: Electromagnetics Simulation. Available online: https://plm.sw.siemens.com/en-US/simcenter/electromagnetics-simulation/magnet/ (accessed on 3 February 2024).
45. FunctionBay, Inc. RecurDyn Overview: Multibody Dynamics Software for Flexible and Rigid Body Analysis. Available online: https://functionbay.com/en/page/single/2/recurdyn-overview (accessed on 3 February 2024).
46. Hexagon. Adams: Multibody Dynamics and Motion Analysis Software for Simulating the Behavior of Mechanical Systems. Available online: https://hexagon.com/products/product-groups/computer-aided-engineering-software/adams (accessed on 16 February 2024).
47. Ansys, Inc. Ansys Mechanical: Finite Element Analysis Software for Structural Analysis and Simulation. Available online: https://www.ansys.com/products/structures/ansys-mechanical (accessed on 16 February 2024).
48. Hexagon. MSC Nastran: Finite Element Analysis Software for Structural Analysis, Including Linear and Nonlinear Static and Dynamic Analysis. Available online: https://hexagon.com/products/product-groups/computer-aided-engineering-software/msc-nastran (accessed on 16 February 2024).
49. Bilgin, B.; Liang, J.; Terzic, M.V.; Dong, J.; Rodriguez, R.; Trickett, E.; Emadi, A. Modeling and analysis of electric motors: State-of-the-art review. *IEEE Trans. Transp. Electrif.* **2019**, *5*, 602–617. [CrossRef]
50. Xu, X.; Han, Q.; Chu, F. Review of electromagnetic vibration in electrical machines. *Energies* **2018**, *11*, 1779. [CrossRef]
51. Levent, A.H.; Lordoglu, A.; Aydeniz, M.G. Design and optimization of permanent magnet synchronous motor for electric vehicle applications. In Proceedings of the 2020 2nd Global Power, Energy and Communication Conference (GPECOM), Izmir, Turkey, 20–23 October 2020. [CrossRef]
52. Rahnejat, H.; Johns-Rahnejat, P.M.; Dolatabadi, N.; Rahmani, R. Multi-body dynamics in vehicle engineering. *Proc. Inst. Mech. Eng. Part K J. Multi-Body Dyn.* **2023**, *238*, 3–25. [CrossRef]

53. Pellerey, P.; Lanfranchi, V.; Friedrich, G. Coupled numerical simulation between electromagnetic and structural models. Influence of the supply harmonics for synchronous machine vibrations. *IEEE Trans. Magn.* **2012**, *48*, 983–986. [CrossRef]
54. Reeves, D. Electric motor noise modeling with Actran. In Proceedings of the 2016 IEEE Transportation Electrification Conference and Expo, Dearborn, MI, USA, 27–29 June 2016.
55. Holehouse, R.; Shahaj, A.; Michon, M.; James, B. Integrated approach to NVH analysis in electric vehicle drivetrains. *J. Eng.* **2019**, *2019*, 3842–3847. [CrossRef]
56. dos Santos, F.L.M.; Anthonis, J.; Naclerio, F.; Gyselinck, J.J.C.; Van der Auweraer, H.; Góes, L.C.S. Multiphysics NVH modeling: Simulation of a switched reluctance motor for an electric vehicle. *IEEE Trans. Ind. Electron.* **2014**, *61*, 469–476. [CrossRef]
57. Kumar, D.; Sambharam, T.; Kottalgi, S.; Mandloi, P.; Kesarkar, O. Electric vehicle powertrain multiphysics NVH simulation. In Proceedings of the IECON 2018—44th Annual Conference of the IEEE Industrial Electronics Society, Washington, DC, USA, 21–23 October 2018. [CrossRef]
58. COMSOL Blog. How to Model Gearbox Vibration and Noise in COMSOL Multiphysics®. Available online: https://www.comsol.com/blogs/how-to-model-gearbox-vibration-and-noise-in-comsol-multiphysics/ (accessed on 26 June 2024).
59. Choi, J.; Ha, T.; Chung, E.C.; Jeong, H.S.; Jung, K.; Harris, O.; Gale, A.; Harvey, T.; Kim, S. *Development of Rumble Noise Analysis Method for Electric Powertrain*; SAE Technical Paper 2023-01-0459; SAE: Warrendale, PA, USA, 2023. [CrossRef]
60. Aghaei, S. Acoustic Radiation of an Automotive Component Using Multi-Body Dynamics. Master's Thesis, KTH Royal Institute of Technology, Stockholm, Sweden, 2020.
61. Shiozaki Shiozaki, H.; Iwanaga, Y.; Ito, H. *Interior Noise Evaluation of Electric Vehicle: Noise Source Contribution Analysis*; SAE Technical Paper 2011-39-7229; SAE: Warrendale, PA, USA, 2011. [CrossRef]
62. Gagliardini, L.; Hamdi, M.A.; Defosse, H. Noise radiation model of a powertrain using an inverse boundary element method and projection on wave-envelope vectors. In Proceedings of the SAE 2003 Noise and Vibration Conference, Traverse City, MI, USA, 5–8 May 2003. [CrossRef]
63. Pennig, S.; Quehl, J.; Rolny, V. Effects of aircraft cabin noise on passenger comfort. *Ergonomics* **2012**, *55*, 1252–1265. [CrossRef]
64. Caprile, J.; Chaufour, C.; Chartrain, P. Efficient methodology for automotive powertrain acoustic radiation analysis. In Proceedings of the 9th International Styrian Noise, Vibration & Harshness Congress: The European Automotive Noise Conference, Graz, Austria, 22–24 June 2016. SAE Technical Paper 2016-01-1794. [CrossRef]
65. Luegmair, M.; Münch, H. Advanced equivalent radiated power (ERP) calculation for early vibro-acoustic product optimization. In Proceedings of the 22nd International Congress on Sound and Vibration, Florence, Italy, 12–16 July 2015; pp. 1–8.
66. Müller, J.; Jacobs, G.; Ramm, M.; Wischmann, S.; Jagla, P.; Berroth, J. Model-based NVH optimization of a tractor drivetrain during different phases of a design adaptation. *Forsch. Ingenieurwesen* **2023**, *87*, 363–373. [CrossRef]
67. Skill-lync. Real-Time Simulation of the HEV Powertrain Using MATLAB & Simulink. Available online: https://skill-lync.com/blogs/real-time-simulation-of-the-hev-powertrain-using-matlab-simulink (accessed on 26 June 2024).