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ANALYSIS OF NVH IN TRACTION MOTOR OF ELECTRIC VEHICLE UNDER SPEED-VARYING OPERATING CONDITIONS

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ABSTRACT

The electric vehicle industry has seen swift advancements in recent years. However, high-frequency electromagnetic and gear whine noises from electric powertrain systems can significantly impact driving comfort, emerging as a crucial noise vibration and harshness (NVH) issue for electric vehicles. This paper presents an NVH simulation analysis for an integrated electric powertrain system under electromagnetic and gear-meshing excitations. The simulation model evaluates the influence of motor torque ripple on whine noise and verifies the simulation method's effectiveness through test results. Additionally, the study reveals the impact of the stator breathing mode on the 48-order whine noise. The paper's main contribution is presenting an NVH simulation method for electric powertrain systems that balances accuracy and efficiency, enabling the early identification and mitigation of whine issues during powertrain development.

I. INTRODUCTION

The automotive industry is currently experiencing a significant shift in its paradigm with electric vehicles (EVs) gaining prominence. Major global automakers are investing heavily in EV production, signaling a strategic shift in their business models. This transition from traditional vehicles to EVs entails substantial changes in powertrain system configurations. While traditional rear-wheel-drive automobiles typically feature an engine–transmission–axle setup, electric rear-wheel-drive vehicles adopt a motor–axle configuration. Despite extensive research on traditional powertrains, there remains a notable gap in understanding the dynamics and vibration characteristics of EV powertrains.

Process of Vibration and Sound Analysis

When an electric vehicle accelerates or decelerates, harmonic excitation forces with distinct order characteristics cause the powertrain housing to vibrate and emit noise. The primary sources of these harmonic excitation forces responsible for whine noise are electromagnetic loads and gear-meshing forces. Electromagnetic loads include forces on the stator teeth and torque ripple on the rotor, the latter of which transfers pulsating harmonic loads to the powertrain housing via the drive system bearings. Gear-meshing forces are dynamic loads produced by interacting gears, also transmitted to the housing through bearings.

In this study, time-domain electromagnetic loads under constant-speed conditions are obtained using 2D electromagnetic field simulations with Maxwell software. Multi-body dynamic simulations provide the time-domain forces on the bearings. An interpolation algorithm generates order loads from these forces. The normal vibration velocity of the powertrain housing is determined using finite element (FE) analysis by applying these order forces to the structural model. The acoustic FE module in Virtual Lab software calculates the acoustic transfer vector (ATV) from the housing's surface vibration velocity to sound pressure at observation points. Finally, sound pressure levels (SPLs) at these points are calculated.

NVH simulation accuracy is influenced by various factors, particularly the modelling accuracy of structural modes. Accurate structural modeling is critical for reliable multi-body dynamic simulation results, affecting computed bearing forces and forced vibration outcomes. A key challenge is accurately modeling the stator, composed of anisotropic silicon steel sheets and parameter-uncertain windings. To enhance accuracy, modal correlation analysis between tested and simulated modes is conducted to calibrate stator parameters before using the FE model for dynamic simulation and vibration analysis. This entire NVH simulation process is outlined in Figure 1.

FE Modeling and Calibration for the Powertrain System

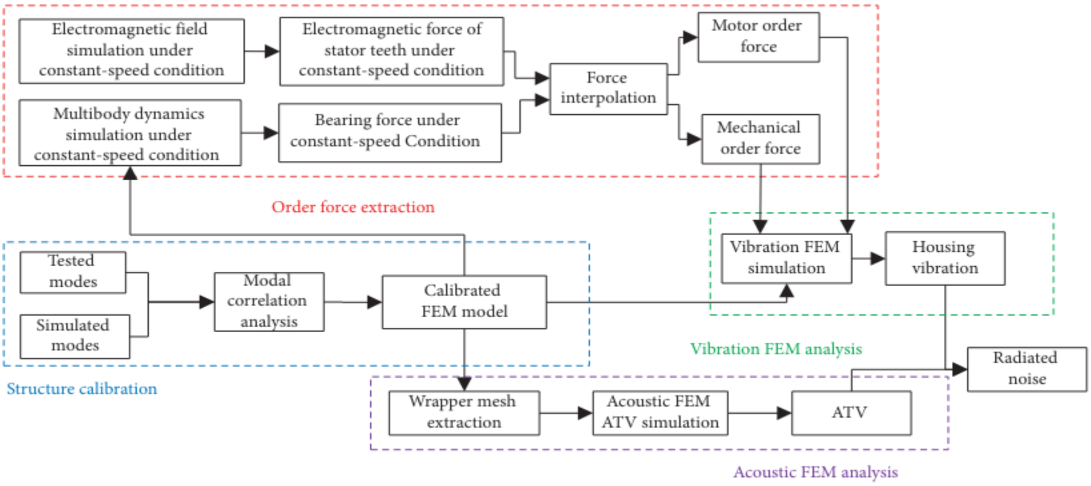


Figure 1: Process of vibration and sound analysis.

Figure 2 shows the 3D structural model used for powertrain NVH (Noise, Vibration, and Harshness) simulation. This powertrain system connects the motor, motor controller, and reducer to the vehicle body through suspensions. A significant challenge in FE (Finite Element) modeling is creating the stator model. At constant speed, the air-gap electromagnetic force follows a periodic pattern in time and angle. When speed varies, this force displays ordered characteristics in the frequency and wavenumber domains. Using a 2D Fourier transform, the air-gap electromagnetic load can be expressed as a series of “force patterns,” each with a specific spatial distribution and rotational frequency. The degree of resonance and resultant electromagnetic noise depends on how well these force patterns align with the stator modes. Close alignment in frequency and shape between a force pattern and a stator mode results in strong resonance and intense electromagnetic noise. Therefore, an accurate FE model of the stator is crucial for precise simulation, necessitating pre-testing of the stator’s natural modes for parameter calibration.

Model calibration involves optimizing parameters to ensure the simulation accurately mirrors the structure's dynamic characteristics, achieving good agreement between simulated and test data regarding modal shapes and frequencies. Calibration can be done manually, which requires adjusting each physical parameter based on personal expertise, making it challenging for complex models. Alternatively, modal correlation analysis can use software like Virtual Lab to automatically optimize parameters after importing test modes. This paper adopts the latter method.

Figure 3 illustrates the stator's FE model, with the winding modeled in two parts: an equivalent isolation layer made of isotropic material with low elasticity modulus, and an equivalent winding made of anisotropic material. Initial material parameters for the stator core and equivalent winding are based on reference [12]. The isolation layer uses polyimide with default properties: density $\rho = 1.2$ g/ml, elasticity modulus $E = 3$ GPa, and Poisson ratio $\mu = 0.35$.

In the modal test, frequency response functions are obtained from transient excitations. The stator, suspended with an elastic slope, is excited using a hammer, and vibrations are measured at 36 points on the stator surface, arranged in three circles of 12 points each. Three axial acceleration sensors capture the vibration signals. Test results are then analyzed in Virtual Lab for correlation and parameter optimization. Figure 4 compares simulated and tested modes, showing modal results with axial order $m=0$ and circumferential orders $n=0, 2, 3$, and 4. The relative error between computed and experimental modal frequencies is less than 6.4%, with correlation coefficients above 0.6, indicating accurate representation of natural vibration characteristics. Other structural parts are assumed isotropic and are not discussed in detail.

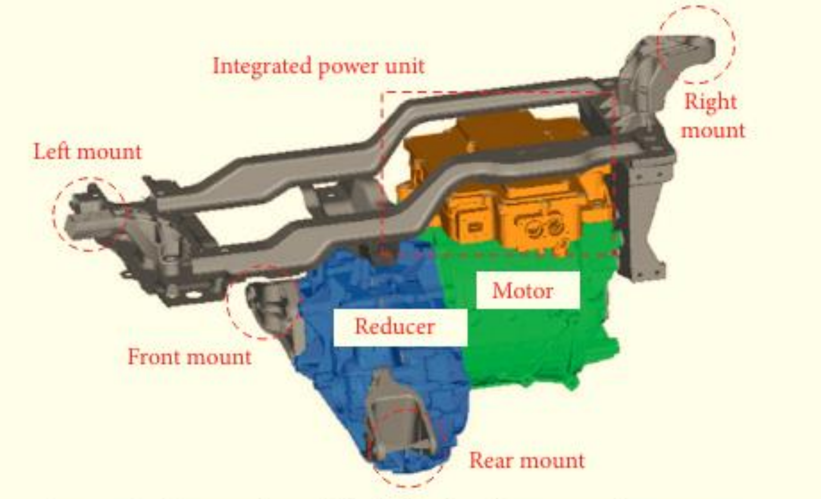


FIGURE 2: Structural model of the electric powertrain system.

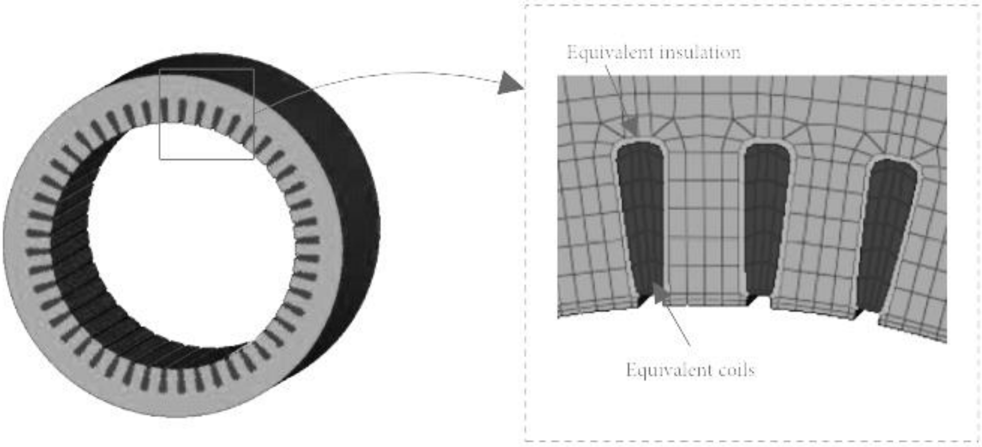


FIGURE 3: FE model of the stator core with winding.

Simulation of Excitation Forces

The NVH performance of the powertrain system varies with running conditions, especially as vehicle velocity and motor torque are often transient in real-world driving. Full-throttle acceleration and coasting deceleration are typically the worst conditions for powertrain whine noise in electric vehicles. Therefore, these two conditions are primarily evaluated for powertrain NVH performance. For instance, under full-throttle conditions, the simulation of vibration and noise orders is conducted for the powertrain system. Initially, electromagnetic and bearing forces under constant-speed conditions are determined, and then order forces for varying speeds are calculated through interpolation.

Electromagnetic Forces under Constant-Speed Conditions

The powertrain system uses a permanent magnet synchronous motor with 8 poles and 48 slots. Finite Element (FE) analysis of the electromagnetic field is performed using Maxwell software for constant-speed conditions, ranging from 1000 rpm to the maximum speed in 1000 rpm increments. Previous research suggests that this step size provides satisfactory accuracy for interpolating electromagnetic force calculations.

Rather than directly using the electromagnetic forces at each tooth's nodes for interpolation and subsequent simulation, equivalent concentrated electromagnetic forces for each tooth are used. This involves converting the node forces on each tooth into a single axial and tangential force, disregarding the circumferential distribution effect. This method slightly reduces simulation accuracy but significantly reduces data volume, enhancing simulation efficiency. The motor's 48 slots are evenly spaced, with electromagnetic force sampled at 48 circumferential points. According to the sampling theorem, Fast Fourier Transform (FFT) can only recognize the forces for the first 24 spatial orders. When using concentrated forces for NVH calculations, forces with spatial orders above 24 ($n > 24$) are ignored. Typically, motor electromagnetic vibration depends heavily on low-order circumferential structural modes. As the order increases, the mode's vibration amplitude decreases with a speed of n^4. Additionally, as the force order increases by multiples of the number of poles, the electromagnetic force amplitude decreases. Thus, using concentrated electromagnetic force has minimal impact on simulation accuracy.

Bearing Forces under Constant-Speed Conditions

The gearbox consists of two pairs of helical gears and a pair of differential gears, generating dynamic forces during gear meshing. These forces are transmitted to the powertrain housing via bearings. Multi-body dynamic simulation is conducted to determine the exciting forces at the bearings under constant-speed conditions. Considering the influence of housing flexibility on dynamic meshing force characteristics, the powertrain housing is treated as a flexible body in the model. Modal condensation is used to reduce housing model degrees of freedom before integrating it with the FE model for improved efficiency.

Order Forces under Varying Speed Conditions

This section focuses on obtaining order forces during acceleration through interpolation. The term "order" denotes the frequency's relation to the rotor's rotating frequency. FFT is used to obtain frequency spectrums of forces, followed by force interpolation between adjacent constant-speed conditions in the frequency domain. Cubic spline interpolation with not-a-knot boundary conditions is employed. Additional speed conditions are included to consider the powertrain housing's natural vibration characteristics' impact on bearing forces. Speeds matching gear engagement order frequencies with housing natural frequencies are selected. Figure 5 illustrates this selection process.

Vibration and Noise Simulation

Vibration Modeling and Loading

Prior to conducting vibration simulation, it's imperative to compute the natural modes of the powertrain system through Finite Element (FE) analysis. Here, Nastran software is employed for modal calculation, followed by importing the results into LMS Virtual Lab for force loading and vibration simulation. Suspension cushions are represented by spring elements, with stiffness coefficients matching the static stiffness of the cushions.

To streamline the process, a specialized program called "Force_gene.exe" is developed. This program automatically generates order forces, aligns them with FE geometry, and produces load files compatible with LMS Virtual Lab for vibration simulation. This automation significantly enhances efficiency and accuracy compared to manual loading. Despite the automated process, it's important to note that the load on each stator tooth, obtained through interpolation calculation, remains a concentrated force. The program further decomposes this concentrated force into numerous point forces distributed across the tooth surface.

Acoustic Simulation

The Boundary Element Method (BEM) is a native technique for simulating acoustic wave problems, especially exterior ones. However, traditional BEM has limitations such as efficiency and memory consumption. To address these, fast accelerated BEM is introduced and applied to large-scale acoustic problems. In this study, acoustic transfer vector (ATV) from powertrain housing vibration to sound pressure response is calculated using acoustic FE simulation in LMS Virtual Lab.

ATV serves as a linear input-output transfer relation between housing vibration and sound field response points. It's influenced by various factors such as housing geometry, acoustic impedance, and signal frequency. Importantly, ATV calculation doesn't require surface vibration velocity, making it efficient for NVH simulation under different operating conditions. Compared to direct vibroacoustic FE methods, ATV method requires only one round of acoustic FE simulation for multiple operating conditions, ensuring consistency and efficiency.

II. RESULTS AND DISCUSSION

Bearing Forces Electromagnetic loads on the motor comprise electromagnetic forces on the teeth and torque ripple on the rotor. While tooth order forces are discussed earlier, torque ripple also contains order components, such as order 8 and order 48, which can be transmitted to the powertrain housing through bearings, causing vibration and noise. Despite torque ripple being smaller than gear-meshing forces, electromagnetic forces on stator teeth often exceed those caused by meshing gears. Consequently, constant torques are used in multi-body dynamic analysis, neglecting torque ripples due to minimal impact on electromagnetic noise simulation accuracy.

Experiment Verification and Analysis

Simulation results are compared with NVH test data to verify accuracy. Tests are conducted in a semi-anechoic laboratory, with microphones and acceleration sensors recording vibration and sound signals under full-throttle acceleration. Comparison between simulation and experimental results shows good consistency, with peak errors and frequency deviations well within acceptable limits. Notably, the 48-order whine noise strongly correlates with the stator's breathing mode resonance, underscoring the importance of accurate stator mode simulation for motor-related noise calculation. Future research could delve into the influence of model parameters on simulation accuracy.

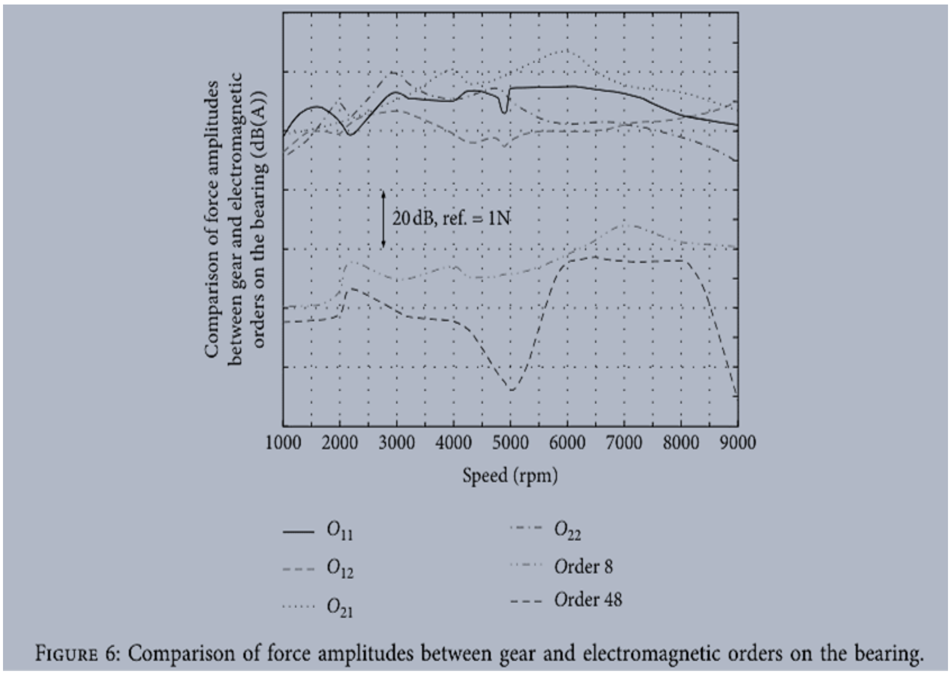
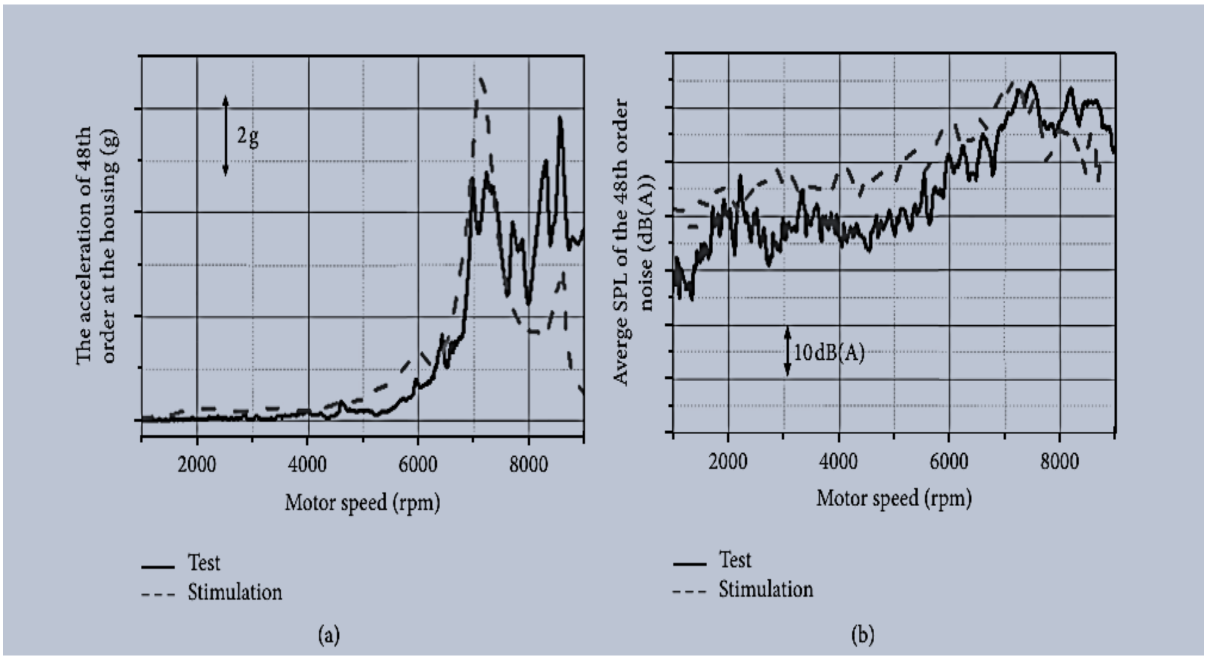


FIGURE 6: Comparison of force amplitudes between gear and electromagnetic orders on the bearing.



(a) (b)

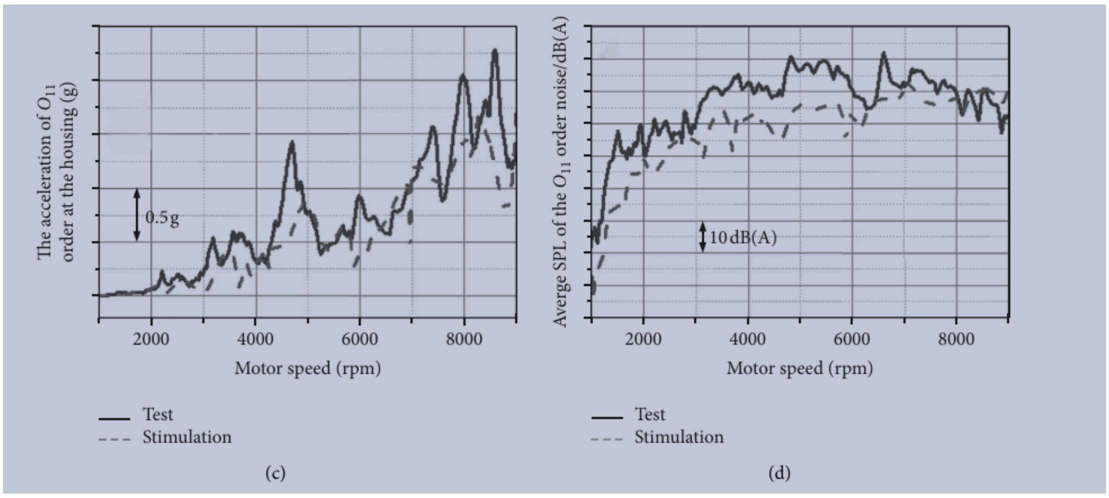


FIGURE 8: Comparison between simulation and test: (a) the acceleration of the 48th order at the housing, (b) average SPL of the 48th order noise, (c) the acceleration of the O_{11} order at the housing, and (d) average SPL of the O_{11} order.

III. CONCLUSION

This study introduces an NVH simulation method tailored for electric powertrain systems operating under varying speeds. Modal correlation analysis is utilized to refine the natural mode representation of the motor stator, thereby enhancing the accuracy of NVH simulations.

The calibrated simulated modes demonstrate a commendable alignment with experimental modes. Across the four key modes analyzed, frequency errors remain within 6.4%, and Modal Assurance Criteria (MAC) values are consistently above 0.6.

Analysis of computed bearing forces reveals that electromagnetic noise stemming from torque ripple is inconsequential compared to that generated by electromagnetic forces acting on stator teeth. Notably, neglecting torque ripple in multi-body dynamic simulations does not significantly compromise electromagnetic Sound Pressure Levels (SPLs).

Vibration and sound results obtained from both simulation and experimental tests exhibit strong agreement. Relative frequency deviation of local peaks between simulation and test curves is below 8%. The peak error of the motor's 48-order SPL is approximately 1 dB (A), while that of order O11 is approximately -8 dB (A).

Moreover, the 48-order whine noise is closely associated with the stator's breathing mode. When the circumferential 0-order component of the 48th-order electromagnetic force aligns with the stator breathing mode in both space and frequency, pronounced local resonance peaks are observed in vibration and sound curves. Exploring the impact of model parameters on simulation accuracy emerges as a promising avenue for future research, promising further insights into optimizing NVH simulation methodologies.

IV. SUMMARY

The automotive industry is currently experiencing a significant shift in its paradigm, with electric vehicles (EVs) gaining prominence. Major global automakers are investing billions of dollars to retool existing factories for EV production, signaling a strategic shift in their business models. This transition from traditional vehicles to EVs entails substantial changes in powertrain system configurations. For instance, while traditional rear-wheel-drive automobiles typically feature an engine–transmission–axle setup, electric rear-wheel-drive vehicles adopt a motor–axle configuration. Despite extensive research on traditional powertrains, there remains a notable gap in understanding the dynamics and vibration characteristics of EV powertrains.

A comprehensive understanding of the vibration and dynamics of EV powertrains is crucial, as these factors significantly impact the durability of powertrain components and contribute to acoustic noise generation. With the increasing market share of EVs, there is a growing imperative to deepen our understanding of the dynamics and vibration phenomena inherent in EV powertrains, which underpin this technological revolution.

Recent studies have begun to investigate the noise and vibration aspects of EVs. For instance, Zeng et al. conducted experimental research on resonance sources and vibration transmission in pure electric buses.

The future development and prospects of reducing NVH (Noise, Vibration, and Harshness) in electric vehicles (EVs) are promising, driven by ongoing technological advancements, research, and growing consumer demands for quieter and more comfortable vehicles.

EV manufacturers and researchers continue to focus on improving electric motor designs to minimize electromagnetic noise and mechanical vibrations. Innovations in motor construction, better magnetic materials, and advanced motor control algorithms will result in quieter and more efficient motors, contributing to reduced NVH levels in EVs.

EV battery packs have a considerable impact on overall NVH performance. Future developments in battery technology may lead to lighter and more compact battery packs, which could reduce the vibrations transmitted through the vehicle's structure. Additionally, advances in battery management systems and thermal management solutions may further minimize noise generation during charging and discharging cycles.

Continued progress in materials science will lead to the development of advanced sound-absorbing and damping materials. Integrating these materials into vehicle design will enhance cabin insulation, reduce road and wind noise, and contribute to a quieter and more refined driving experience.

As autonomous driving technology evolves, there will be an increased focus on passenger comfort and experience. Reduced human intervention may allow for smoother driving patterns, optimizing regenerative braking and minimizing sudden jerks and noise associated with traditional driving styles.

Governments and municipalities are increasingly addressing noise pollution and promoting quieter urban environments. Noise-reducing infrastructure, such as noise barriers and improved road surfaces, will help reduce external noise and contribute to a quieter overall driving experience for EV users.

V. REFERENCES

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