Recent progress in battery electric vehicle noise, vibration, and harshness

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Abstract
As battery electric vehicle (BEV) market share grows so must our understanding of the noise, vibration, and harshness (NVH) phenomenon found inside the BEVs which makes this technological revolution possible. Similar to the conventional vehicle having encountered numerous NVH issues until today, BEV has to face many new and tough NVH issues. For example, conventional vehicles are powered by the internal combustion engine (ICE) which is the dominant noise source. The noises from other sources were generally masked by the combustion engine, thus the research focus was on the reduction of combustion engine while less attention was paid to noises from other sources. A BEV does not have ICE, automatic transmission, transfer case, fuel tank, air intake, or exhaust systems. In their place, there is more than enough space to accommodate the electric drive unit and battery pack. BEV is quieter without a combustion engine, however, the research on vehicle NVH is even more significant since the elimination of the combustion engine would expose many noise behaviors of BEV that were previously ignored but would now seem clearly audible and annoying. Researches have recently been conducted on the NVH of BEV mainly emphasis on the reduction of noise induced by powertrain, tire, wind and ancillary system and the improvement of sound quality. This review paper will focus on recent progress in BEV NVH research to advance the BEV systems in the future. It is a review for theoretical, computational, and experimental work conducted by both academia and industry in the past few years.

Keywords
Electric vehicle, NVH, noise control, vibrations, sound quality

Introduction
The automobile industry is in the process of a major paradigm shift, and electric vehicles (EVs) are gaining momentum. Leading automotive corporations have
announced an investment of billions to convert an old factory into one dedicated to the production of electric vehicles.\textsuperscript{1} This shows that the largest automakers in the world are starting to shift their business model to include EV production. As EV market share grows, our understanding of the NVH phenomena occurring inside EVs must also grow to enable this technological revolution. Traditionally, a vehicle is powered by an internal combustion engine, which is the dominant noise source. Noises from other sources are generally masked by the combustion engine. Thus, the research focus was on the reduction of combustion engine noise while less attention was paid to noises from other sources. A BEV does not have combustion engine, automatic transmission, transfer case, fuel tank, air intake, or exhaust systems. Consequently, there is plenty of space to accommodate the electric drive unit and battery pack. BEVs are more silent because of the absence of a combustion engine. Thus, research on NVH in BEVs is even more significant given that the elimination of the combustion engine will expose many noise behaviors that were previously ignored but could now become clearly audible and annoying. Recent research progress in BEV NVH, including powertrain, tire/road, wind, and ancillary system noises, are reviewed in this paper.

**NVH in BEV powertrain**

Studies were recently conducted on NVH of BEV powertrains. The main emphasis was on the reduction of noise induced by the asynchronous or synchronous motor, gear, and inverter, and the improvement of sound quality. For example, Zeng et al.\textsuperscript{2} demonstrated an efficient analytical strategy comprising order analysis, operating deflection shape, and transfer path analysis for identifying resonance sources and vibration transmission for a purely electric bus. Using this strategy, they found that resonance is mainly induced by the second-order excitation associated with the driveline. In addition, vibration transfer paths from the driveline to the electric bus floor are quantitatively determined by this strategy. Lennström et al.\textsuperscript{3} studied the effect of the spatial resolution of acoustic transfer functions (ATFs) on the estimated interior noise from an electric rear axle drive. They also demonstrated that the characterization of ATFs is critical and effective to provide a correct estimation of BEV interior sound pressure level. Fang and Zhang\textsuperscript{4} investigated the impact of harmonic-order and switching noises radiated by a pulse width modulation (PWM) fed electric powertrain on sound quality. Through vibroacoustic experiments, they showed that the powertrain noise contains two types of acoustic components. The first type is harmonic-order noise, including electromagnetic and gear whine noises. The second type is switching noise. They also discovered that the harmonic-order noise played a major role in contributing to the sound quality at low speeds. The impact of inverter switching noise on the sound quality becomes evident at medium and high speeds with the growth of switching current harmonics. Li et al.\textsuperscript{5} analyzed the electromagnetic noise of the permanent-magnet motor of an electric city bus at the start and during acceleration using simulations. They suggested a method for
noise control of electric buses. They also determined the vibration characteristics of the motor in the range of its operating speed. In addition, these authors optimized and improved the motor structure to suppress the electromagnetic noise radiated by the motor. Dupont and Saucy\textsuperscript{6} developed a simulation process and optimization approach of the noise radiated by electric motors. This method allows for optimization of the noise level over the whole speed range or at targeted critical speeds, with emphasis on the geometry definition of the active parts of the electric motor. Holehouse et al.\textsuperscript{7} developed an approach to NVH analysis in electric vehicle drive-trains. The comprehensive drivetrain model was developed and compared with test data. This model can account for electro-mechanical sources of excitation including motor and gear excitations. This methodology can predict and avoid potential NVH problems early in the design process. Wegerhof et al.\textsuperscript{8} developed an NVH validation methodology for complex elastic multibody simulation models with application to an electrified drivetrain. This methodology speeds up the experimental validation. He et al.\textsuperscript{9} developed a new integrated electromagnetic NVH analysis approach for an automotive traction motor and successfully validated this approach at all dominant motor orders. This approach can predict the induction motor noise and vibration performance in early design stage and aid in motor topology optimization by changing the rotor bar, pole number, and slot counts. They also developed a new equivalent approach that can largely reduce the computational time required to compute the electromagnetic force over transient response. Rane and Deshmukh\textsuperscript{10} discussed various types of electric powertrain mounts on their different contributions to the NVH using ADAMS simulation. They demonstrated that the conventional mount would not meet NVH requirements for electric powertrains and showed the optimization and design approach for electric powertrain mounting. Sarrazin et al.\textsuperscript{11} utilized combined electric experimental measurements to study the NVH performance of electric motors. They mainly studied the differences between various types of motors, that is, permanent-magnet synchronous machines versus switched reluctance machines. Chandrasekhar et al.\textsuperscript{12} specifically investigated the influence of current harmonics on the 6-th and 12-th electrical orders of the torque ripple and electric motor whine noise using statistical correlation and regression analysis based on data obtained from dynamometer testing and finite element analysis (FEA). He\textsuperscript{13} developed a multi-stage system level model to study the influence of key design parameters, such as EM force coupled with structural modes, motor mounting design, drive unit ribbing, and stiffness optimization, on electric-motor NVH performance of a BEV. They also identified key design concepts and parameters that have significant influence on the sound power radiated from the drive unit. They subsequently optimized electric motor designs for improved BEV noise performance. Wang et al.\textsuperscript{14} explained BEV NVH performance and some key technologies for NVH improvement. In addition, they explained the fundamental NVH behavior of an electric motor, i.e., in an electric motor, the dominant NVH phenomenon is the whistling noise subjected to electromagnetic forces and amplified by the powertrain structure. They also showed that current simulation technology can predict the whistling noise levels of an electric motor up
to 4500 Hz. They demonstrated that in the low motor speed range, the dominant whistling noise of an electric motor is due to the coupling between the 24-th-order tangential electromagnetic forces and the torsional mode of the motor stator assembly. Concerning the high motor speed range, the dominant whistling noise of an electric motor is associated to the coupling of radial excitations of 48-th order with the radial breathing mode of the motor stator assembly. Diez-Ibarbia et al.\textsuperscript{15} performed a comparison between transfer path analysis and operational path analysis on BEVs. They performed the comparison between these two methods by considering eight structure-borne paths from the BEV powertrain and suspension points to the BEV cabin. The outcomes of these publications are mainly the development of new methodologies for BEV powertrain NVH analysis and improvement using experimental and numerical ways. The numerical ways mainly include using finite element or analytical approach for the calculation of dynamic excitations, conducting dynamic simulations using 3D finite element or analytical approaches, and performing acoustic simulations using boundary element method (BEM), finite element method (FEM) or analytical method. The developed numerical methodologies were focused on the powertrain level and are reliable and tested. The experimental ways mainly include using order analysis and operating deflection shape to identify the vibration source and using transfer path analysis (TPA) to determine the vibration transfer path in a BEV. The results of these publications are general outcomes for effective diagnosis and treatment on BEV powertrain NVH issues.

**Tire/road noise**

Given that silent BEVs became popular recently, the reduction of the vehicle’s road noise is gaining relevance. As far as the noise generation mechanism is concerned, Forsse´n et al.\textsuperscript{16} developed a tool for tire–road noise auralization of electric cars in a pass-by situation. The tool allows for simulation and auralization of pass-by sounds for arbitrary tire–road combinations considering dense road surfaces. The resulting sounds from this new tool are perceived in similar terms to recordings in pleasantness. Jung et al.\textsuperscript{17} studied the performance of a control algorithm of local active noise using direct measurements of acoustic responses in a vehicle. This new algorithm is an effective method to reduce broadband random road noise in a vehicle cabin and can address noises at frequencies higher than those that can be controlled with a global active control system. Kosaka et al.\textsuperscript{18} stated that decreasing the stiffness of vehicle suspension could reduce the road noise but would worsen the driving stability. Therefore, they proposed a new approach to reduce the BEV road noise by optimizing the suspension geometry. Ishihama et al.\textsuperscript{19} summarized the views of a tire noise committee regarding the technical challenges on tire NVH and accompanying performance. They stated that road noise is one of the most significant factors for future BEV product quality and NVH technology related to tires would progressively become more significant. They also clarified the technical challenges required for introducing next-generation tires and future requirements of tire noise performance. Wysocki et al.\textsuperscript{20} stated that for BEVs, one of the
significant noise sources is road noise, which is transmitted from the tire through the suspension to the vehicle cabin. To solve the road noise problem, they proposed a new approach that can automatically adapt the vehicle FEM models to changes in vehicle suspension so that the suspension layout can be automatically optimized for minimizing the road noise. Cao et al.\textsuperscript{21} performed a study on exterior noise contribution for BEVs. They showed that tire noise is a major contributor for BEV exterior noise.

The outcomes of these publications are with emphasis on the development of new methods for suppressing road noise in BEV vehicle cabin. The methodologies are mainly divided into two categories, that is, the optimization of suspension and active control algorithm of broadband random road noise, and are general outcomes for BEV road noise optimization.

**Wind noise**

Wind noise is a major contributor to the vehicle noise and becomes even more significant as the powertrain noise is reduced by conversion to BEVs. In addition, a silent interior environment for voice activation systems gains relevance. Musser et al.\textsuperscript{22} addressed the challenges of aero-vibro-acoustics (AVA) modeling and simulation for vehicle wind noise applications. They identified the types of computational fluid dynamics (CFD) analyses that are suitable for vehicle vibro-acoustic simulations to predict wind noise. Ying-jie et al.\textsuperscript{23} applied unsteady CFD to simulate the exterior flow field around the vehicle and applied FEA to model the vehicle body structure for computing the vehicle’s interior acoustic response. Using this AVA strategy, they found that the sound pressure level (SPL) response at driver’s ear locations is mainly caused by the wind turbulence pressure fluctuation at the side window instead of an aerodynamic noise source. In addition, they also discovered that the differences in SPL among driver’s location and passengers’ locations are minor. Baudet et al.\textsuperscript{24} developed a new numerical process upon the coupling of two models. With the first model, they computed the air flow and pressure around the vehicle using the lattice Boltzmann method. Using the second model, they applied FEA to simulate the vibrations and noise radiated by the lateral window subjected to the excitation of dynamic pressure from the first model. They validated this new approach by comparing with wind tunnel measurements. Herpe et al.\textsuperscript{25} developed a statistical energy analysis (SEA) method to predict the sound transmitted through a flexible plate that is pressured by the turbulent wave of a vehicle’s rear-view mirror. They found that the acoustic pressure acting on the plate is very low compared with the fluid pressure loading. However, this pressure cannot be ignored given that the non-resonating plate modes would offer an efficient transmission path for the acoustic excitation below the plate coincidence frequency.

The SEA approach\textsuperscript{25} is preferred in an acoustical transmission manner for wind noise prediction and suited for fast predictions at the early vehicle design stage, however, an explicit method coupling CFD and FEM\textsuperscript{23} is preferred at the later vehicle design stage for design validations since it is most reliable and tested although most computationally expensive.
Ancillary system noise

The number of studies on ancillary system noise for BEVs is small. Park and Lee\textsuperscript{26} found that the cooling fans designed for dissipating the heat emitted from the battery, motor, and generator constitute one of the main noise sources for BEVs. They applied a hybrid approach to study the broadband noise source from a shrouded automotive cooling fan using acoustic analogy based on the surface pressure computed by CFD. This new approach is a general outcome and can aid in reducing the broadband noise in automotive cooling fans. Guo and Zhou\textsuperscript{27} focused on solving the abnormal noise and vibration problem of electric vacuum pump when the vehicle is stationary. They utilized a FEA model to optimize the electric vacuum pump (EVP) mount to reduce the sound pressure level in the vehicle cabin at driver’s right ear. The test data confirmed this improvement, thereby enhancing the passenger’s ride comfort. The result is not a general outcome and will be dependent on the specific design and application of EVP mount. Zhang et al.\textsuperscript{28} proposed a neural network model for evaluating the sound quality of an axial piston pump of BEV based on both subjective and objective evaluations. They demonstrated that the sound quality model can predict sound quality of axial piston pumps with good accuracy and efficiency. This method sets the foundation for the improvement of sound quality in BEV hydraulic displacement pumps. The proposal neutral network model is a general approach and outcome for accurately predicting and evaluating the sound quality of axial piston pumps.

Effective solutions for reducing BEV NVH

Some existing effective solutions for reducing BEV noise and vibration and methods that are widely used in engineering are outlined and summarized.

Firstly, motor vibration can be suppressed by using motor structural parameter optimization and motor controller design approaches. For example, Qin et al.\textsuperscript{29} summarized the NVH suppression technologies for motors including structural motor parameter optimization and controller design. As for the method of structural motor parameter optimization, motor vibration can be reduced by changing the design of the motor stator- and rotor-poles. The switched reluctance motor vibration can be effectively reduced by using a skewed stator pole. Motor vibration induced by the electromagnetic force can be reduced by the design of a trapezoidal pole on the hexagon-round yoke. Passive damping devices, for example, an improved stator mounting bolt design, can help reduce the motor whine. The torque ripple of a motor can be reduced by the modified three-phase cable design. As for the method of controller design, compared with the method of motor structural optimization, it is generally less difficult to implement. The control methods, including traditional, modern, and intelligent control methods, applying the algorithms of Proportion, Integral and Differential (PID), Linear Parameter-Varying (LPV), Model Predictive Control (MPC), and Fuzzy Control are effective approaches and solutions for suppressing motor vibrations.
Secondly, the vibrations at the bearings can be suppressed by optimizing the bearing quality, design parameters, and operation mode. For example, Migal et al.\textsuperscript{30} performed experimental studies on effective solutions for reducing the vibration levels of BEV asynchronous motors by examining the influence of bearing quality, size, and operation mode. They discovered that by increasing the bearing accuracy class from P0 to P5, they can dramatically reduce the vibration levels at the bearing unit by up to 16 dB. They also found that a decrease in rotating frequency of bearings or in loading can lead to a decrease in bearing vibration levels. In addition, optimizing the preload of bearings can reduce the bearing unit vibration levels by 5–8 dB in the region of 160–6300 Hz for most frequencies. Optimizing the clearance of the bearing installation into the housing can reduce the vibration levels of the bearing unit by 5–10 dB for most vibration frequencies as shown in Figure 1.

Thirdly, gear design optimization can be an effective approach for suppressing BEV noise and vibration. Wang et al.\textsuperscript{31} conducted both simulation and experimental studies and demonstrated that the new teeth surface and back (TSB) modification method is an effective solution in reducing the BEV planetary gear powertrain (PGT) transient torsional vibrations, vehicle jerk, and ride discomfort, especially at high speed condition, as illustrated in Figure 2. In addition, Hu et al.\textsuperscript{32} studied the hybrid electric vehicle noise and vibration problems in the electric driving mode. They applied the frequency analysis of the experimental results and identified the gear meshing as the main source of noise and vibration. Then they suppressed the vehicle vibration and noise by optimizing gear parameters including mesh stiffness, tooth error, and pitch error. Furthermore, Lei et al.\textsuperscript{33} developed a new approach using multi-objective optimization algorithm for suppressing electric bus gearbox noise and vibration effectively and efficiently. This new approach was designed to minimize the noise excitation sources including transmission error and tooth surface load.

\begin{figure}[h]
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\caption{Effect of the bearing fitting clearance in the housing on the vibration levels of the bearing unit with the rotation speed of (a) 1450 and (b) 2000 r/min. Curves 1–4 respectively correspond to the frequencies of 160, 200, 250, and 630 Hz.\textsuperscript{30}}
\end{figure}
Fourthly, optimization of the BEV suspension structure can be an effective approach for suppressing the vibration induced by the uneven road condition. For example, Qin et al. developed a new method for suppressing vibrations of BEVs with in-wheel switched reluctance motors (SRMs) by applying a novel dynamic vibration absorbing structure (DVAS) design. Compared with the conventional switched reluctance motor (SRM)-suspension system, the novel DVAS design including both tire type and chassis type as shown in Figure 3 achieves the improvement of 35% in ride comfort and 30% in road handling.

Summary

BEV NVH was actively explored by researchers in the last few years, including powertrain noise, road noise, wind noise, and ancillary system noise. Considering the main global automotive market trends for BEVs, research on BEV NVH will
not become redundant anytime soon. Similar to conventional vehicles, which encountered numerous NVH issues, BEVs have to face many NVH issues. Many of the operational components, for example, batteries and cooling systems of electrical motors, are devoted to electric powertrains and can be a potential field for future research. In addition, BEVs give rise to innovative application areas for the treatment and insulation of annoying high-frequency noise from the electric motor, gears, as well as road and wind noise, which were previously dismissed in the NVH research for conventional vehicles. More research efforts should be made in this area, for example, by creating more effective models and algorithms and reducing annoying high-frequency noise in BEVs. It would also be a challenge for the experimental investigation as well as for the numerical investigation. New modeling techniques and validation procedures would come up due to this complexity since most of the conventional methodologies for ICE were optimized for low frequency range of maximum few hundred Hz and the human perception is affected by the tonal high frequent sound. Moreover, the goal of BEVs is to make lighter, more silent, and more energy-efficient vehicles. Therefore, future research can aim at designing and optimizing lightweight NVH components that integrate aerodynamic and acoustic functions. In addition, for the pedestrian safety, the Acoustic Vehicle Alerting System (AVAS) is included in BEVs. However, the AVAS can have an impact to the vehicle cabin sound, which can be a future research focus. Finally, active noise control (ANC) and sound design can be an alternative for suppressing the cabin noise, masking unwanted sound, and improving the sound quality without the requirement of physical changes to the vehicle.

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