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Noise Reduction Methods in the Vehicle Industry: Using Vibroacoustic Simulation for Sustainability

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To achieve sustainability goals, such as greenhouse gas emissions and environmental noise reduction, continuous innovation plays a key role in the vehicle industry. The noise emitted by vehicles negatively impacts both the environment and public health, making the development of noise reduction strategies crucial. Vibroacoustic simulation methodologies provide an opportunity to optimise vehicle power transmission systems by reducing the emitted noise level. Besides, the energy efficiency and performance of the vehicles can be improved by vibroacoustic simulations. In this research, a vibroacoustic simulation methodology is presented, focusing on the power transmission systems of vehicles. This approach integrates the Finite Element Method and Multibody Dynamics simulations with vibroacoustics to identify and redesign noisy components even during the conceptual design stage. This approach tackles the challenge of high-frequency tonal noise for electric vehicles, using psychoacoustic reviews to enhance passenger comfort. Key tasks involve electromagnetic force analysis in the drivetrain, structural vibration simulations, and noise reduction strategy optimisation using machine learning algorithms to reduce the reliance on physical prototypes. Capturing the current momentum of the industry, machine learning capabilities in vibroacoustic models can help engineers identify sources and eliminate or mitigate noise in the early design phase. Reducing the number of prototypes leads to more sustainable design processes. Our study shows the noise level can be reduced by 3-5 dB. This is particularly important in the context of electric vehicles, where high-frequency tone noise should be reduced, benefiting both passengers and their environment. Improving these factors is in line with the goals of the United Nations and improves the quality of urban life. Our research highlights the importance of vibroacoustic simulation and opens new directions in the field of noise reduction, promoting the spread of sustainable transport solutions.

1. Introduction

Sustainability is a crucial requirement for the vehicle industry today. Annual reduction of emissions and vehicle noise levels requires constant innovation and the development of new technologies with the aim of rendering cars less harmful to the environment and more respectful of public health. For instance, Ur et al. (2020) explored the environmental implications of vehicular noise pollution, while Yoo et al. (2021) focused on the environmental consequences of vehicular noise pollution. Similarly, Pusztai et al. (2021) examined driving strategies for optimizing energy-efficient lightweight vehicles. Protecting the environment from vibration pollution and its derivatives plays a significant role in the environmental sustainability of the population. Noise reduction strategies are required to meet the sustainability goals. Vibroacoustic simulation approaches provide a new tool for the prediction and optimization of power transmission systems. Simulation tools are significant for minimizing noise emissions and increasing fuel efficiency (Research and Markets, 2019). Electric vehicles (EVs) have been increasing in popularity as a sustainable transport solution. High-power electric powertrains pose new requirements for reducing noise - particularly with regard to high-frequency, tonal noise - and psychoacoustic qualities (Lu et al., 2024). Shaik Mohammad (2023) presented new tools based on artificial intelligence (AI) and machine learning (ML) to predict road noise of EVs, while Schirmacher (2010) focused on more traditional noise reduction methods such as active noise reduction and virtual sound design. AI and ML technologies have been developed, making it possible to simplify or replace traditional vibroacoustic simulation chains. These technologies are useful in a wide range of applications, from simplifying simulation preparation to replacing the

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entire simulation chain, optimizing the simulation step by step, and estimating hard-to-determine indirect parameters. AI and ML allow the simulation data analysis in a more detailed manner and should be able to make predictions more accurately. Thus, we can expect shorter iteration cycles and better results when forming noise reduction strategies. Support vector regression (SVR) and other ML algorithms can enhance the sensitivity of nonlinear acoustic signals for the detection of structural defects (HPCwire, 2023). The research objective is to show 1) how significant the role vibroacoustic simulation can play in vehicle noise reduction, especially with EVs, and 2) how AI and ML technologies can be potentially used in simulation workflow. Our results support the dissemination of sustainable transport solutions, reducing environmental damage from the automotive industry, which cuts down the quality of urban life. Our results help to promote sustainable transport, resulting in the boosting of community health and overall well-being. The fact is that vibration simulation is costly in terms of computational demand when one looks at classical vibroacoustic simulation methods. When dealing with ML and AI-based models, which learn from the data, they can recognize and predict a pattern from the data, unlike the physical model, which needs the entire model to simulate the output using the data. Not only does this type of approach provide more energy efficiency and reduce even the hardware demands for simulation in an environmentally friendly way, but Jeon and Kim (2021) also illustrated a decrease in computational costs for Computational Fluid Dynamics (CFD) computing. Li et al. (2022) investigated AI-enabled assessment of vibroacoustic modulation on bolt loosening. Yin et al. (2022) worked on approaches to combine deep learning with high-performance computing (HPC) simulations. Finally, Cunha et al. (2022) presented an exhaustive overview of ML algorithms in structural dynamics and vibroacoustic analysis. A vibroacoustic simulation brings together engineering disciplines: mechanical behaviour and acoustic behaviour in-vehicle noise reduction.

A critical issue for EVs is, of course, the management of Noise, Vibration, and Harshness (NVH), especially as the tonal noise of the electric powertrain can be heard more directly into the passenger compartment without the masking effect of the internal combustion engine (ICE), whose sound many find pleasant. Numerous works investigate the vibroacoustic of EVs (Król et al., 2023), per-type approach and simulation methods (Xiang), and vibration and sound analysis methods of recent technical and simulation techniques (Kaselouris, 2023). This research builds on the latest methods, seeking a new direction in vibroacoustic simulations by merging AI/ML techniques, specifically focusing on power transmission systems noise in vehicles. The study showcases the integration of mechanical and vibroacoustic modelling alongside AI-driven optimisation algorithms, enabling the identification of noise sources early in the design. One of the main aims is to deliver greener manufacturing by reducing physical prototypes. A psychoacoustic analysis can also help mitigate high-frequency tonal noise, which is crucial for EVs, improving both passenger perception and reducing external vehicle noise levels. Additionally, the study aims to assess the environmental and energy-saving effects of these simulation methods, contributing to sustainable automotive development in line with current industry trends.

2. Theory

The basic principle of vibroacoustic simulation is to combine the modelling of mechanical and acoustic systems. Vibroacoustic simulations identify the source and propagation of noise and vibration, allowing targeted noise reduction measures to be taken. Finite element method (FEM) and multibody dynamics (MBD) simulation are important integrated modelling techniques for noise and vibration analysis of vehicles (Hamiche, 2021). The use of FEM and MBD simulations greatly contributes to improving design methodology and vehicle acoustics and brings huge benefits to EVs facing significant acoustic challenges (Sethuraman, 2018). The electromechanical simulation can deliver an accurate calculation and analysis of the primary source of the motor vibration - the electromagnetic forces. To identify the noise source and to develop plans to eliminate it, we need to have a full and accurate model of the electromagnetic phenomena.

Calculations of electromagnetic fields and waves in a time-varying and spatial domain require solving Maxwell's equation, which plays a fundamental role in many electronic simulation techniques (Xu et al., 2022). This simulation is used to significantly reduce the noise of a car and achieve optimum performance. Li et al. (2024) analysed the radial electromagnetic force and vibration characteristics of permanent-magnet synchronous motors, while Wang et al. (2023) focused on electromagnetic force modelling for noise and vibration control in EVs. MBD simulation is used to create a simulation of the vehicle's motion and dynamic behaviour. While an MBD simulation takes place, the interactions between the engine, gears, suspension, and all other components within the vehicle are modelled under dynamic loads. These interactions result in structural vibrations and noise. MBD simulations permit a relational analysis of the structure and motion characteristics of the vehicle, which goes a long way in the development of strategies to reduce noise. They assist in the vehicle industry as simulations can support the vehicle's design mechanisms to improve performance (Shiiba et al., 2012).

The vibration and deformation of the vehicle structure are modelled by the FEM. Subsequently, the structure of the vehicle is represented by a large number of small finite elements, and the equations of motion are solved in FEM simulations too. Ultimately, this endows the method with full resolution of the dynamic structure and the ability to evaluate noise reduction measures. The implications and design improvements in vehicle noise reduction, in general, are very effective with the use of FEM tools (Sung and Nefske, 1984). Boundary Element Method (BEM) is also a numerical method that models the propagation of noise in space. With the help of the method, it is possible to determine the sound pressure levels emitted by noise sources. To analyse the spatial acoustic loads of the environment. Another advantage of the BEM method is that it limits the calculations to the surfaces, reducing the calculation capacities. The use of this method can help to optimize vehicle design processes and reduce noise levels efficiently (Kirkup, 2019).

Traditional Multiphysics vibroacoustic simulations require high computational power. Computer-Aided Engineering (CAE)-based Multiphysics vibroacoustic simulations require high computational power. Helping these problems with certain methods, such as ML-based models, drastically reduces the computational demands. Using their operational method, they can learn and recognise complex patterns from the available data and make predictions from it, eliminating the need to run the full physical model, which is significantly less machine-intensive. The smaller hardware resources allow for lower power consumption, making the simulation side of the design and optimisation process more sustainable. For example, Jeon and Kim (2021) demonstrated computational cost saving in CFD simulation by using ML, while Li et al. (2022) explored the concept of AI in the evaluation of bolt loosening via vibroacoustic modulation. Yin et al. (2022) combined deep learning with HPC simulations. Cunha et al. (2022) provided a summary of ML techniques in structural dynamics. Multiphysics vibroacoustic simulation, a multidisciplinary tool, simulates both the mechanical and acoustic aspects of noise emissions in vehicles. Many studies focus on vibroacoustic analysis of EVs. FEM (Finite Element Method) and MBD simulations capture structural vibrations, noise propagation, and radiation. In the mechanical modelling phase, vehicle components, such as gears, engines and power transmission systems, are represented in a mesh of finite elements, simulating vibrations and deformations. In the case of EVs, electromagnetic analysis, which models the electromagnetic fields generated by the engine using Maxwell's equations, is one of the first images. These fields interact with the mechanical components of the electric motor and cause various vibrations in the structure. The structural vibrations are caused by the interactions of the components, which are predicted using MBD simulations parallelly to FEM. It then simulates the propagation of sound waves in the air resulting from structural vibrations using the BEM, calculating the sound pressure levels. The psychoacoustic analysis evaluates the effect of high-frequency sound noises on human perception. Psychoacoustics also takes into account factors such as loudness and sharpness. The final phase involves optimisation using ML techniques, which refine the model based on simulation data. ML algorithms predict noise levels for different design configurations, allowing iterative optimisation to reduce noise.

This entire workflow process results in a comprehensive vibration-acoustic model. These models are used to predict mechanical vibrations and acoustic responses, allowing the localisation of noise sources and the creation of noise reduction strategies. Outputs typically include vibration mode shapes, sound pressure levels (SPLs) and frequency spectra for key operating points. Król et al. (2023) investigated the vibroacoustic in EV motors, and Xiang (2017) studied the modelling and optimisation of vibroacoustic behaviour with COMSOL Multiphysics. Kaselouris (2023) analysed motion-driven interactions in vibroacoustics using coupled FEM-BEM simulations. The literature highlights the need for appropriate vibration acoustic simulations to reduce noise levels in automotive applications. The modelling of the acoustic behaviour of vehicle components under dynamic loading relies on different holistic approaches of Multiphysics simulation techniques. These techniques successfully identify noise sources. AI and ML-based models have since been used to further optimise these simulations to take less computational load, increasing sustainability. Future research will also explore synergies between these methods to optimally manage vehicle noise levels, both in terms of efficiency and sustainability.

3. Translated with DeepL.com (free version) Discussion

In terms of sustainability, the advantages of vibroacoustic simulation:

- **Material and energy savings:** Using traditional (CAE) methods, fewer physical prototypes are needed.
- **More accurate results:** Simulation using CAE techniques allows accurate identification of noise sources and effective noise reduction strategies.
- **Shortened development cycles:** CAE methods enable more iterations, which accelerates innovation and development. Testing multiple design variations leads to more optimized designs in a shorter time.
- **More sustainable manufacturing processes:** CAE helps produce higher quality manufacturing processes by identifying and correcting problems in the early stages of the manufacturing steps.

3.1 Combining ML with vibroacoustic simulations for sustainability

Integrating ML into vibroacoustic simulations offers significant benefits in sustainability.

Smaller hardware requirements: Conventional vibroacoustic simulation systems are known for their relatively high hardware requirements. ML-based models can significantly reduce hardware requirements:

- **Improved computational methods**: ML algorithms are able to recognize and predict complex patterns based on the available data without the need to run the entire physical model.
- **Faster run time:** ML models can run much faster than traditional simulation methods because they learn and predict from only the relevant data. This leads to sustainability in the following ways:
- **Faster iteration cycles**: Shorter runtimes enable faster iteration cycles in design processes.
- **More efficient development process:** Shorter simulation times allow more design cases to be tested.
- **Quicker and more detailed noise and vibration analyses:** ML algorithms are able to analyse large amounts of data and identify complex patterns.
- **Complex parameters determination:** ML models can identify complex indirect parameters that are challenging or impossible to obtain through direct measurements.
- **Data-driven decision making:** Using ML-based analytics, engineers can make data-driven decisions.

Sustainable manufacturing processes: The implementation of ML methods in vibroacoustic simulations helps to design more sustainable production processes:

- **Reduced material usage:** Optimized designs use less material and fewer resources during the manufacturing process, resulting in less waste and a reduced ecological footprint.
- **Energy-saving manufacturing:** Efficient design processes and the need for fewer prototypes reduce energy consumption, contributing to more sustainable manufacturing.

3.2 Application of AI and ML algorithms

The use of ML methods can speed up the labour-intensive preparatory work of the simulation and replace the entire simulation chain. Complex parameters that are not even measured directly can be determined.

- **Simplification and acceleration of simulation preparatory work:** ML methods can be utilised to support the automation and speed up the meshing process, replacing the traditional pre-processing workflow.
- **Simulation chain replacement:** ML-based solutions can completely replace a traditional simulation chain (Maxwell, MBD, FEM, BEM), speeding up the simulation and saving resources, as shown in Figure 1.
- **Replacement of a step in the simulation chain:** ML models can serve as a replacement for a specific step in the simulation chain. For example, a ML model can be used instead of FEM, optimising the process and providing more accurate results.
- **Calculation of parameters that are difficult to determine:** ML models help estimate complex factors, such as indirect parameters that are not easily measured. These models are capable of implicitly determining derived parameters that are inferred from other measured data.

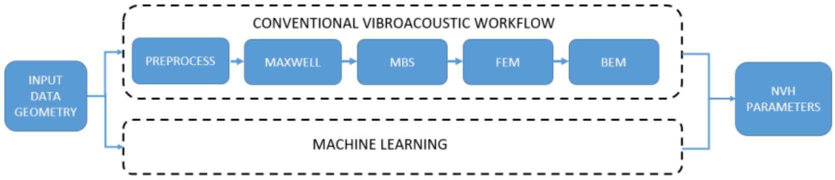

Figure 1: Comparison of conventional vibroacoustic workflow and ML integration

3.3 Predictive modelling

The application of ML allows:

- **Detection of influential production variables**: Identifying which production variables have a bigger influence on the noise level of the gear and investigating the correlations between these variables in the final machining process of the gears and the noise levels measured in end-of-line acoustic tests. This method improves the accuracy of production processes and efficiently recognises noise sources.
- **Development of predictive models:** Creating models that predict the expected noise level of the engine based on production parameters. These models help design and optimise production processes to minimise noise levels.
- **Detection and resolution of faults:** Identifying and resolving faults in the early stages of production processes. This approach avoids many mistakes and increases production efficiency, directly contributing to sustainable manufacturing processes.

4. Results

To analyses and mitigate the structural vibrations and noise propagation in the transmission of vehicle components, CAE-based Multiphysics vibroacoustic simulations have effectively combined the electromagnetic analysis method, the FEM, MBD and BEM simulations. These coupled simulation methodologies provided detailed insight into the vibration behavior of gear drives under different operating conditions. The results of the electromagnetic analysis using Maxwell's equations showed how the excitation electric fields generated by the EV motors contribute to the mechanical vibrations. These excitations are characteristic at operating frequencies between 1-2 kHz, values that are consistent with the concerns about tonal noise identified in the psychoacoustic analysis. FEM simulations in the mechanical analysis revealed pronounced vibration amplitudes in power transmission systems. This was particularly the case in high torque regions where gear interactions produced higher mechanical stresses. The MBD simulations also showed that certain gear configurations amplified structural vibrations, especially at other loads at higher speed operating conditions. BEM simulations were used in the acoustic modelling phase. The method was used to evaluate SPL inside and outside the vehicle. The acoustic analysis showed a potential noise reduction of 3-5 dB with the optimised designs, especially when dealing with high-frequency sound noise. The mid- and high-frequency tonal noise and disturbances, which are typical of EV engines in general, significantly affected the overall perceived loudness and sharpness of the sound, which has psychoacoustic relevance. Following traditional CAE simulations, ML algorithms were used to iteratively optimise the design parameters. Also, to predict noise levels for different geometric configurations. The developed ML models have played a key role in refining noise reduction strategies and micro-geometric optimisation of the gear. The ML model not only replaced the traditional machine-intensive simulation processes but was also able to replace a simulation step. This saves time and energy, which contributes to sustainability. The results obtained with the optimised designs show that noise reductions of up to 5 dB can be achieved. Noise reduction also contributes to improving passenger comfort and reducing environmental noise. The output results of simulations included vibration mode shapes, frequency spectra, and SPL data from the overall modelling process. These provided information for targeted noise reduction strategies based on mechanical and psychoacoustic analyses. The results show that, overall, Multiphysics optimisation and the integration of different methodologies, such as ML, showed significant potential for reducing noise emissions from EVs.

5. Conclusions

This article examines the significance of vibroacoustic simulation techniques in the automotive industry from a sustainability point of view. Optimising the external and internal noise levels of road vehicles has become relevant not only for the environment but also for public health and quality of life. Vibroacoustic simulations combined with ML provide a robust framework for noise reduction in EV drivetrains in the design phase. The methodology identified the critical high-vibration areas of the drive chain elements. ML was used for iterative optimisation, improving noise reduction strategies by optimising the gear geometry. The discoveries showed that the noise level can be further reduced even with the optimised design. Noise reduction from driveline components results in a quieter, more comfortable driving experience, which is becoming more and more prominent in the field of vehicle features and vehicle development these days. The results could help improve sustainable car manufacturing, where vibroacoustic and ML simulations could reduce the need for physical prototypes and minimise resource use. The transition to EVs has brought new challenges in the area of NVH, especially high-frequency sound noise that is not masked by sounds from the internal combustion engine. Integrating or replacing AI/ML technologies in vibroacoustic simulations can effectively address these challenges. Namely, by increasing the efficiency of noise reduction techniques, enabling the early detection of noise sources in the design phase, and reducing the dependence on physical prototypes. All of this can lead to more environmentally friendly and cost-effective manufacturing processes, in line with wider sustainability and environmental protection goals. By reducing the need for physical prototypes, they can reduce both material and energy consumption. This all contributes to reducing the ecological footprint of vehicle production. These developments are in line with the UN's sustainability goals, which support the creation of greener and quieter cities. Data-driven research and development can improve the efficiency of simulations. Vibroacoustic simulations can be positioned as an effective tool in dealing with industrial noise emission challenges.

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