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PERCEPTUAL IMPACT OF PARTICLE DAMPERS ON ELECTRIC VEHICLE POWERTRAIN NOISE

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Abstract

Electric vehicle powertrains exhibit prominent tonal and structure borne noise components originating from power electronic modules and electromagnetic excitations. Although particle dampers have been widely investigated for vibration attenuation, their application in electric vehicle powertrains with respect to structure-borne acoustic radiation remains limited. To the authors' knowledge, psychoacoustic investigations of particle dampers in electric vehicle powertrains have not yet been reported. This study investigates the integration of a particle damper within the lid of a power electronic module to mitigate acoustic and psychoacoustic parameters. A cavity integrated into the module lid was partially filled with rubber granulate and experimentally evaluated on an electric drive test bench. Acoustic measurements were conducted under representative operating conditions, and psychoacoustic metrics were calculated according to ECMA 418-2, including loudness, tonality, and fluctuation strength. Results demonstrate a broadband reduction in sound pressure level. More importantly, the particle damper significantly reduces time varying loudness and tonal prominence. Since both sensations adversely affect the sound quality, it is likely that the integration of a particle damper leads to measurable improvements in perceived acoustic quality. The findings highlight the potential of particle dampers as an effective passive solution for noise vibration and harshness optimization in electric powertrains.

Keywords: *particle damper, electric power electronics, sound quality, noise vibration and harshness, psychoacoustic metrics*

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1. Introduction

Noise, vibration, and harshness (NVH) continue to represent significant challenges in automotive engineering, as they directly influence passenger comfort, component durability, and compliance with increasingly stringent regulatory requirements. With the ongoing transition toward electric vehicles (EVs), the nature of NVH has undergone a notable shift. In particular, the absence of conventional combustion noise has made previously less perceptible noise sources more prominent, thereby increasing the complexity of noise control strategies. At the same time, psychoacoustic parameters such as tonality and loudness have gained greater importance, as they strongly affect the perceived acoustic quality of electric drivetrains. The electric drive unit, which typically consists of high-speed electric motors, gearboxes, power electronic modules (PEMs), and battery systems, represents a major source of vibroacoustic emissions in EVs. Within this system, both the motor and the PEM contribute to high-frequency excitations that propagate through the structure in the form of structure-borne noise. In particular, pulse width modulation (PWM)-induced harmonics in PEMs generate radial electromagnetic force waves, which can interact with structural modes of the housing. This interaction may lead to the excitation of structural resonances, thereby amplifying noise radiation [1]. These effects are further intensified by the use of lightweight and thin-walled casing structures, which, while beneficial for efficiency and weight reduction, tend to exhibit lower structural damping and higher vibration transmissibility. As a result, the overall acoustic performance of the system can be adversely affected. In this context, the present study investigates the application of particle damping as a passive noise reduction technique for PEMs. The design of the PEM considered in this work is illustrated in Figure 1. Particle damping relies on energy dissipation mechanisms arising from frictional contacts and viscoelastic interactions between granular materials and the surrounding structure. These mechanisms enable effective attenuation of vibrations over a broad frequency range, making particle dampers a promising solution for improving the vibroacoustic behavior of electric drive components.

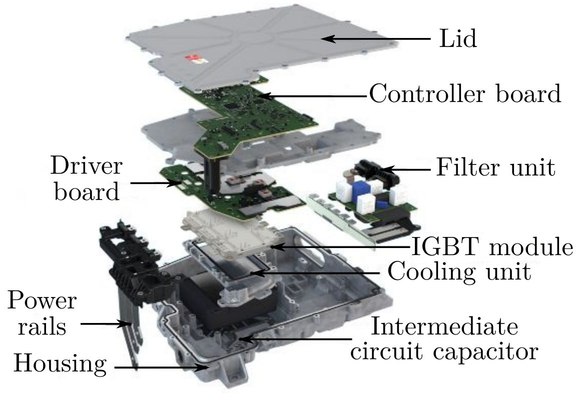

Figure 1: A detailed illustration of the physical layout of a power electronic module [2].

NVH reduction has been widely addressed through gear, motor, and bearing optimization. Lei et al. [3] showed that gear micro-geometry optimization reduces noise from meshing errors, while Hu et al. [4] identified planetary gear interactions as dominant noise sources and demonstrated noise reduction through parameter optimization. Migal et al. [5] achieved vibration reductions up to 16 dB via improved bearing design. For power electronic converters, strategies such as active-passive isolation [6] and acoustic shielding [7] are used, but are often limited by complexity, added mass, and packaging constraints. Vibroacoustic metamaterials offer improved noise reduction compared to conventional damping layers, albeit with significant mass penalties [8]. Particle dampers have been explored across applications, though with mixed acoustic performance. Akbar et al. [9] reported reduced vibration but increased noise due to particle impacts. Wang et al. [10] showed improved acoustic behavior using fine granular materials, though without detailed measurement methodology. Field studies, such as rail applications, demonstrate reduction up to 8 dB at higher frequencies, with reduced effectiveness at low frequencies and possible resonance effects [11]. Despite these developments, passive damping solutions for compact subsystems such as inverters remain limited. Most approaches focus on motors, gears, and bearings, while inverter noise is typically addressed through shielding or isolation, which may be impractical in compact designs. Moreover, conventional particle dampers with metallic particles can increase airborne noise due to high-energy impacts, highlighting the need for alternative materials that reduce both sound pressure levels and psychoacoustic effects. In this context, particle dampers using recycled rubber granulate offer a promising solution, combining effective damping with lower mass and improved durability [12], [13]. Building on previous work in wind turbine applications [14], [15], this study extends the established design framework to electric vehicle powertrains without additional optimization.

Therefore, this study investigates particle dampers filled with recycled rubber granulate from end-of-life automotive tires for reducing sound emissions in electric vehicle powertrain systems and evaluating their influence on psychoacoustic parameters such as loudness and tonality. The granulate (Figure 2) has a polydisperse size distribution with a bulk density of 465 kg/m^3.

Figure 2: Rubber granulate with median particle size range of 4.6 mm used in the particle damper.

2. Implementation of particle damper in PEM

Figure 3 presents the PEM assembly integrated with the electric motor, with particular emphasis on the incorporation of the particle damper within the lid structure. The figure provides an overview of how the damper is accommodated in the available cavity space of the lid. The distribution of the rubber granulate is not arbitrary but is constrained by the internal geometry of the lid as well as the limited installation space[1]. As indicated in Figure 3, a clearly defined region within the PEM housing remains intentionally unfilled. This area is reserved for electronic components and associated connections, making it unsuitable for the placement of granular material. Consequently, the particle damper can only be implemented in the remaining accessible volume, leading to a non-uniform distribution of the granulate. To ensure reliable operation, it is essential to prevent any escape of particles under dynamic loading conditions. For this purpose, the cavity containing the rubber granulate is securely enclosed using a thin steel sheet with a wall thickness of 0.15 mm. This enclosure not only guarantees proper containment of the particles but also maintains the structural integrity of the lid while minimizing any additional mass or stiffness effects.

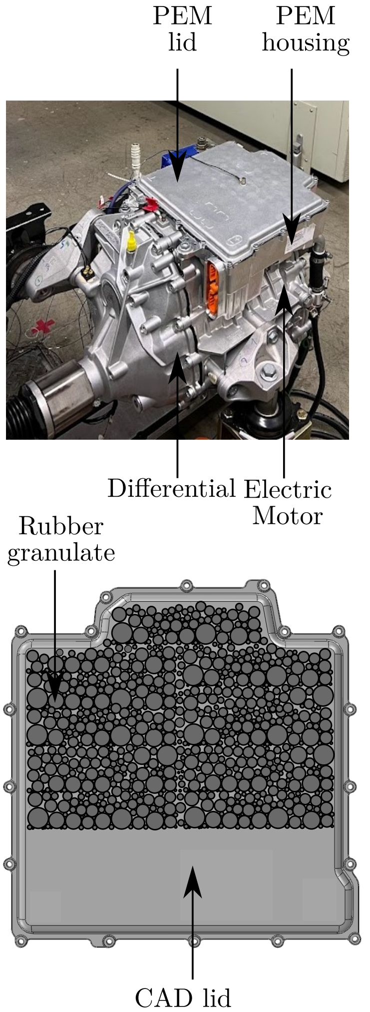

Figure 3: Above: A PEM mounted on an electric drive system. Below: A CAD model of the PEM's lid, partially filled with rubber granulate.

3. Experimental setup

The experimental setup used to investigate the effect of the particle damper on acoustic and psychoacoustic parameters is shown in Figure 4. The e-drive test bench is designed to house various subsystems, including the dynamometer, measurement devices, and control systems, in an efficient and organized manner. To minimize potential noise disruptions and ensure an optimal testing environment, all subsystems, except for the power supply unit, dynamometer, and the test bench control system, are enclosed within an anechoic chamber. The test bench is divided into two distinct zones, namely the testing zone (anechoic chamber and brake room) and the operator zone. The testing zone, which contains all the primary subsystems, is strictly restricted during testing to uphold the integrity and safety of the procedures. In contrast, the operator zone accommodates crucial equipment such as the power distribution cabinet, test control cabinet, and inverter cabinet, which allow for centralized monitoring of test activities. Additionally, the layout is designed with modularity and scalability in mind, enabling the seamless integration of additional components or subsystems as required by evolving customer demands or regulatory standards.

The assessment of the particle damper's performance under real-world operating conditions was conducted through a two-phase experimental approach. In the first phase, the e-drive was operated at full load while performing a rotational speed sweep, beginning at 50 RPM and progressively increasing to $10,000$ RPM. This phase was designed to evaluate the damper's effectiveness across a wide range of operating speeds typically encountered in e-drive applications. The test also sought to identify the critical speed and corresponding frequency range where vibration and sound emission issues arise in electric vehicles. Furthermore, it aimed to verify whether these findings were consistent with the speed and frequency range specified by our industrial partner.

In the second phase, the e-drive was subjected to a stationary test, operating at a fixed rotational speed and torque, evaluated under a full-load testing scenario. This specific test condition was chosen to simulate a critical scenario in which vibration and sound emission issues pose significant challenges to driving comfort. By maintaining these parameters constant, the test provided valuable insights into the particle damper's ability to mitigate vibrations under demanding operating conditions.

4. Results

The application of the particle damper leads to a clear reduction in sound pressure levels across a broad frequency range from 200 Hz to 8 kHz Hz (see Figure 5). Compared to the reference configuration (without particle damper), a consistent decrease in spectral amplitudes is observed over most of the investigated frequency bands. The most pronounced noise mitigation occurs within the critical frequency range of 800–1100 Hz, where the particle damper effectively suppresses dominant tonal components. In terms of overall performance, the total sound pressure level integrated over the full frequency range (100–10,000 Hz) is reduced by 4.5 dB. A more significant reduction is achieved within the critical band (800 Hz - 1100 Hz), where the sound pressure level decreases by 6.5 dB. These results indicate that the particle damper not only provides broadband noise attenuation but is particularly effective in reducing prominent tonal contributions, which are typically associated with increased perceptual annoyance.

4.1. Effect of particle damper on loudness

Figure 6 shows the time-dependent loudness N(t), calculated according to ECMA-418-2 using ArtemiS SUITE, for both the reference and particle damper configurations. After a brief transient phase, both signals reach a quasi-steady state. The reference condition exhibits an overall loudness of approximately 5.9 soneHMS, whereas the particle damper configuration

[1] Detailed information on the backside geometry of the lid cannot be disclosed due to confidentiality restrictions

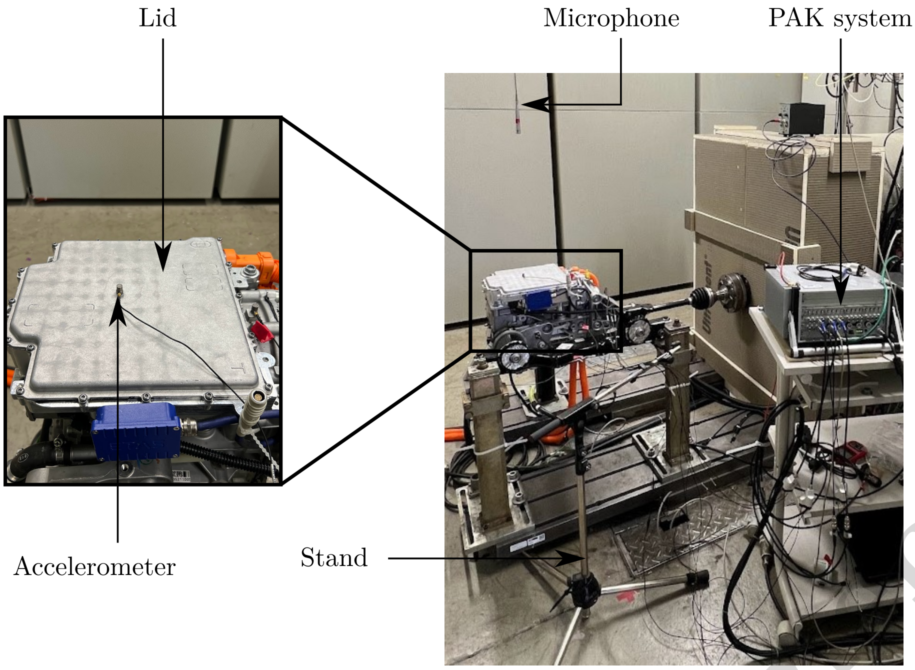

Figure 4: Experimental setup for assessing the vibration attenuation performance of the particle damper on the e-drive PEM.

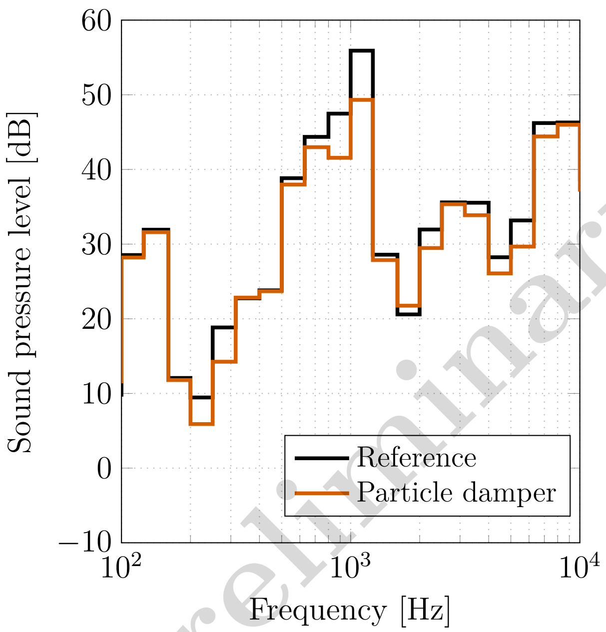

Figure 5: Third-octave sound pressure level spectrum of the e-drive comparing the reference configuration and particle damper.

stabilizes at around 4.9 soneHMS. This corresponds to an average reduction of approximately 1 soneHMS, equivalent to a decrease of about 15–17% in perceived loudness. From a psychoacoustic perspective, this reduction should be peerceptible. The observed decrease in loudness indicates that the particle damper effectively reduces acoustically relevant energy within frequency regions that contribute strongly to human auditory perception. Furthermore, the low temporal variation of the loudness signals indicates stable operating conditions, with no additional modulation introduced by the particle damper. Instead, a consistent reduction in perceived sound intensity is achieved over time. Overall, the results demonstrate that the particle damper provides not only a physical reduction in sound emissions but also a meaningful improvement in perceived sound quality through a significant decrease in loudness.

4.2. Effect of particle damper on tonality

Figure 7 presents the time-varying tonality T(t), calculated according to ECMA-418-2 using ArtemiS SUITE, for both the reference and particle damper configurations. After a short transient phase, both signals reach a quasi-stationary state with only minor temporal fluctuations. The reference condition exhibits a mean tonality of approximately 1.6 tuHMS, whereas the particle damper configuration stabilizes at around 1.2–1.3 tuHMS. This corresponds to a reduction of about 0.3–0.4 tuHMS, equivalent to approximately 20–25%. From a psychoacoustic perspective, this reduction is highly significant, as tonality represents the perceptual prominence of distinct spectral components above the masking threshold. The observed decrease therefore indicates a reduced salience of tonal components typically associated with electromagnetic excitation and switching harmonics in electric powertrains. Since tonal components strongly influence perceived annoyance, even moderate reductions should lead to noticeable improvements in sound quality. The consistent reduction over the entire measurement duration further confirms that the particle damper effectively attenuates tonal contributions rather than only reduc-

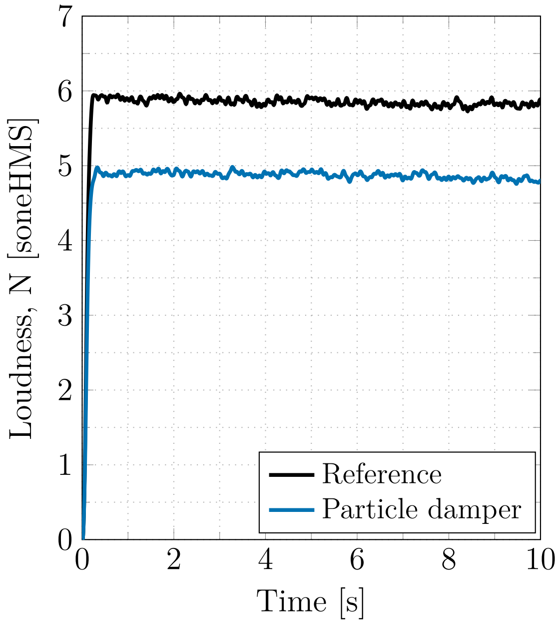

Figure 6: Time-dependent loudness N(t) [soneHMS] obtained using the ECMA-418-2 Hearing Model for the reference condition and the particle damper condition.

ing broadband energy. Overall, the results demonstrate that the particle damper provides a meaningful improvement in perceived acoustic quality by reducing tonal prominence, complementing the observed reduction in loudness and sound pressure level.

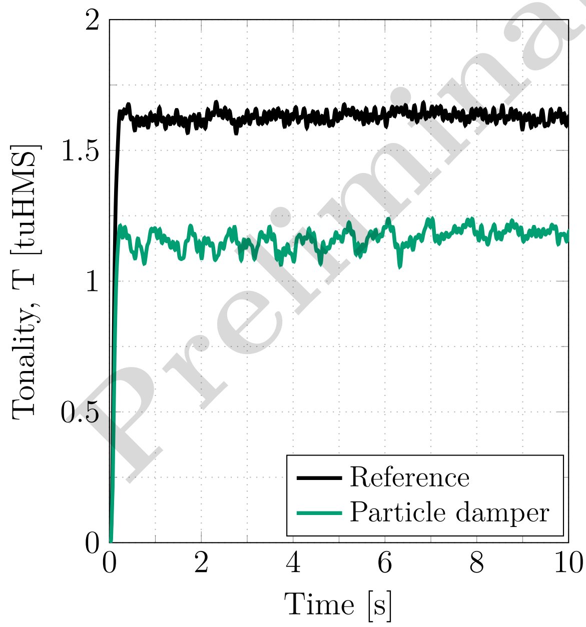

Figure 7: Time-varying tonality T(t) [tuHMS] calculated according to ECMA-418-2 for the reference condition and the particle-damped configuration.

4.3. Effect of particle damper on fluctuation strength

Figure 8 presents the time-varying fluctuation strength F(t), calculated according to ECMA-418-2. After the initial transient, both conditions reach a quasi-stationary state, indicating the presence of low-frequency amplitude modulation. The reference configuration exhibits values of approximately 0.16–0.18 vacilHMS, whereas the particle damper configuration stabilizes at around 0.06–0.08 vacilHMS. This corresponds to a reduction of about 0.09–0.11 vacilHMS, or approximately 55–65%. Fluctuation strength quantifies the perceptual impact of slow amplitude modulations, typically below 20 Hz, which are perceived as wavering or pulsating characteristics and contribute significantly to annoyance in technical sounds. In electric powertrains, such modulations are commonly associated with torque ripple, electromagnetic force variations, and control-induced effects. The substantial reduction in F(t) indicates that the particle damper effectively suppresses these modulation components, thereby reducing modulation depth and perceptual salience. The consistent decrease over time confirms a stable and robust effect. From a psychoacoustic perspective, reductions of this magnitude should be clearly perceptible and correspond to a smoother and less intrusive acoustic impression. Consequently, the particle damper should enhance sound quality not only by lowering sound levels but also by mitigating temporally varying modulation features that strongly influence perceived annoyance.

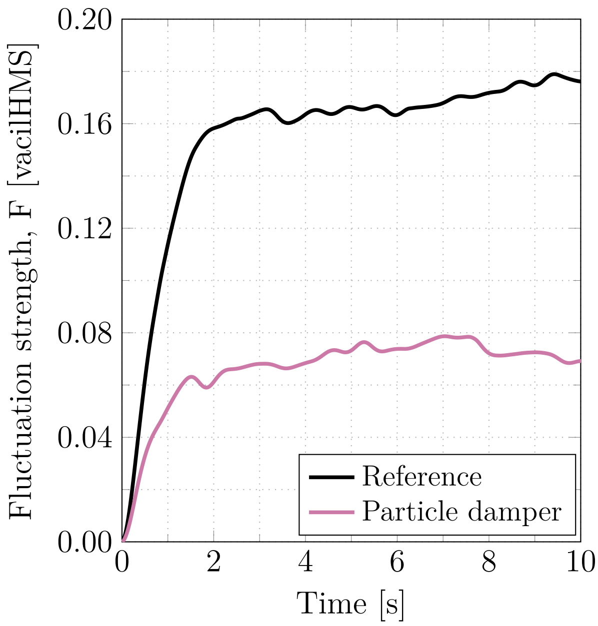

Figure 8: Time-varying fluctuation strength F(t) [vacilHMS] calculated according to ECMA-418-2 for the reference condition and the particle-damped configuration.

5. Conclusion and outlook

This study investigated the application of a particle damper integrated into the lid of a power electronic module for noise reduction in electric vehicle powertrains. The results demonstrate that the particle damper provides effective broadband noise reduction, with a total sound pressure level decrease of up to 4.5 dB and a maximum reduction of 6.5 dB within the critical frequency range. In addition to conventional acoustic evaluation, a central objective was to assess whether particle damping also influences psychoacoustic parameters relevant to perceived sound quality. Beyond these physical improvements, a significant impact on psychoacoustic metrics was observed. The particle damper reduced loudness, tonality, and fluctuation strength in a consistent and perceptually meaningful manner. In particular, the reduction of tonal components and low-frequency modulation effects indicates a clear improvement in perceived sound quality, which is especially important for electric vehicles where such features strongly influence user perception. These findings confirm that particle dampers are not only effective for vibration and sound pressure level reduction but should also contribute to improving psychoacoustic sound quality. Therefore, they represent a promising passive solution for NVH optimization in compact electric powertrain components such as power electronic modules. In future work, controlled listening tests will be conducted to further validate the psychoacoustic benefits and to establish a more accurate perception-based evaluation framework. These investigations will enable a deeper understanding of the relationship between measured psychoacoustic parameters and subjective human perception, supporting the development of optimized design guidelines for particle dampers in electric vehicle applications.

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