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Active Masking of Tonal Noise using Motor-Based Acoustic Generator to Improve EV Sound Quality

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Abstract

Electric motor whine is one of the main noise sources of electric vehicles (EVs). Without engine masking noise, high pitch tonal noise from electric motor can be highly annoying and raise sound quality issues for electrified propulsion systems. This paper describes a patented new technology that controls electric motor to actively mask annoying high-pitch tonal noise by (i) controlling electric motor to create complementary low order tones to enrich sound complexity and distract high pitch tones; (ii) controlling motor to generate random dithering noise to raise masking noise floor and reduce tone-to-noise ratio around tonal targets; (iii) combining complementary injection at low frequency and dithering at high frequency for enhanced masking. This new technology enables controlling masking noise level, frequency, order and bandwidth as a function of motor torque and speed for most effective masking. The new active masking technology is successfully implemented and validated using GM's Bolt EV in motor dyno and vehicle cabin noise tests. Jury tests are performed that confirm enhanced EV sound quality with slight impact on motor torque and efficiency.

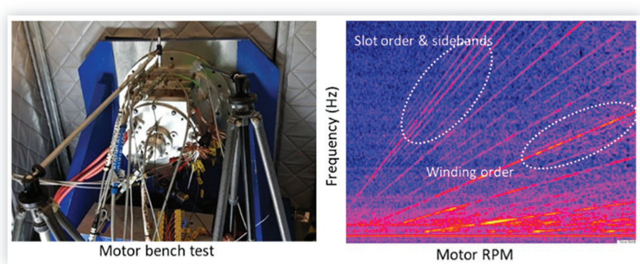
Introduction

Electrification is becoming the future of the automotive industry. Customers' increasing demand for environmentally friendly transportation, more stringent CO2 regulation across the globe, and tax incentives for new energy vehicles in many countries all motivate automotive manufactures to develop low emission and energy efficient vehicles [1]. Electric motor whine is one of the most dominant noise sources for Battery Electric Vehicles (BEVs) and Hybrid Electric Vehicles (HEVs) when it is operating in the EV mode, especially at low speed conditions. Although absolute EV noise dB level is relatively low, their tonal sound character can be annoying without engine masking noise. Such high pitch whine can raise tonal noise concerns, which may adversely affect the sound quality or acoustic rating for EVs.

Conventional strategies to reduce electric motor whine include performing electro-magnetic (EM) optimization to reduce EM noise sources, stiffening electric Drive Unit, its mount design and vehicle structural path, as well as adding damping treatments and acoustic blanks [2-6]. The common goal of all these methods is to reduce the noise dB level on the receiver end. However, common EV design trends are heading towards high-power-density motors, high-speed-ratio reduction gears, light-weight materials and integrated motor-transmission-power electronics. All lead to higher EM noise sources, less design spaces for path optimization and more stringent mass/cost constraints for damping treatment. These contribute to significant NVH challenges for electrified propulsion systems and make the conventional strategies less effective. Therefore, it is highly desirable to develop novel techniques that can improve the sound quality in a cost-effective manner, without necessarily reducing the motor whine dB levels. This paper describes a patented new technology developed at General Motors that controls electric motor to create authentic powertrain sound, which can be controlled to effectively mask unpleasant tonal whine and enhance EV sound quality.

General Motor's Chevrolet Bolt EV is used as a case study to develop and demonstrate the new technology. Figure 1 shows the electric motor whine measured in a motor fixture test bench, where the torque ripple order (or stator slot order) and its sidebands are identified as primary masking targets. Figure 2 shows measured electric Drive Unit noise, where electric motor whine is present among dominant noise sources with additional transfer gear orders. Measured cabin noise during a moderate drive away event in Figure 3 also contains

FIGURE 1 Bolt EV electric motor fixture dyno test



also successfully generated to enrich the sound signature and distract passengers' attention from the high pitch motor whine.

Recorded EV sound files were assessed by the NVH team for sound quality. Jury tests show over 93% reported difference in sound quality before and after AMAG injection. About 87% felt active masking helped to reduce the tonal feeling or sharpness of the motor whine. About 75% jurors concluded the AMAG improved sound quality and considered the tonal motor whine less annoying with active masking.

Impact on Motor Performance

The new AMAG technology injects additional currents in the motor controller, and its impact on electric motor performance are benchmarked using the Bolt EV motor. Figure 14 shows the AMAG impact on motor nominal torque over a range of motor torque. It is observed that the dithering based active masking has negligible impact to motor torque, while the complementary tonal injection leads to a few Nm of torque loss, which is roughly 1% of the nominal motor torque. Figure 15 shows the AMAG impact on motor efficiency over a range of motor torque. The dithering based active masking has less than 0.5% impact to motor efficiency, while the complementary tonal injects leads to slightly more than 0.5% impact to motor efficiency. Combining both strategies results in up to 1% reduction in motor efficiency.

FIGURE 14 Impact of active masking on Bolt EV motor torque

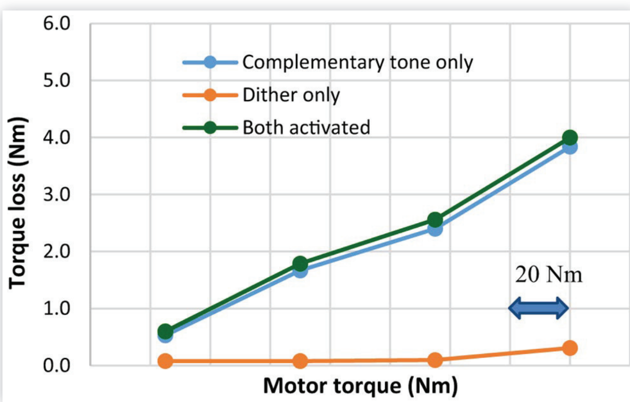
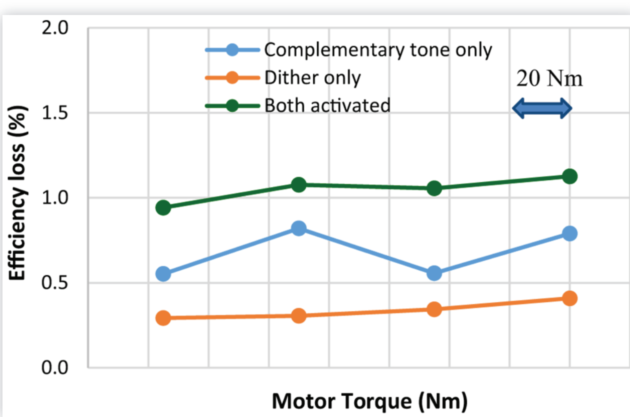


FIGURE 15 Impact of active masking on Bolt EV motor efficiency



Note that the AMAG technology can be activated and customized only at specific motor torque and rpm range, where tonal motor whine is identified as an issue. These typically occur at high torque and low speed conditions, where the tone-to-noise ratio is relatively high but take a very small portion of typical fuel economy driving cycles. Therefore, the AMAG impact on EV performance and fuel range is mostly negligible.

Summary/Conclusions

This paper describes a new motor-based acoustic signal generator technology that is capable of creating authentic electric drive sound to actively mask high pitch electric motor whine. The signal generator can create complementary low order tones to enrich sound complexity and distract high pitch tones. It can also generate broadband dithering noise to raise masking noise floor and reduce tone-to-noise ratio around tonal targets. Both strategies can be activated simultaneously for enhanced masking. This new technology allows the masking noise level, frequency, order and bandwidth to be controlled as a function of motor torque and speed for most effective masking. The new technology has been successfully implemented and validated using GM's Bolt EV in motor dyno and vehicle tests. Jury tests are performed that confirm enhanced EV sound quality with small impact in motor torque and efficiency. Additional tests have confirmed the new technology can be generalized across various vehicle platforms with different motor hardware designs. The new technology is used to improve motor sound quality for GM's battery electric and hybrid electric vehicles. Future work includes to study potential interactions with motor control algorithms, and to integrate the motor-based AMAG technology with vehicle infotainment system based MSE technology to achieve optimal active masking.

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