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Multiple target sound quality balance for hybrid electric powertrain noise

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ABSTRACT

The integration of the electric motor to the powertrain in hybrid electric vehicles (HEVs) presents acoustic stimuli that elicit new perceptions. The large number of spectral components, as well as the wider bandwidth of this sort of noises, pose new challenges to current noise, vibration and harshness (NVH) approaches. This paper presents a framework for enhancing the sound quality (SQ) of the hybrid electric powertrain noise perceived inside the passenger compartment. Compared with current active sound quality control (ASQC) schemes, where the SQ improvement is just an effect of the control actions, the proposed technique features an optimization stage, which enables the NVH specialist to actively implement the amplitude balance of the tones that better fits into the auditory expectations. Since Loudness, Roughness, Sharpness and Tonality are the most relevant SQ metrics for interior HEV noise, they are used as performance metrics in the concurrent optimization analysis, which, eventually, drives the control design method. Thus, multichannel active sound profiling systems that feature cross-channel compensation schemes are guided by the multi-objective optimization stage, by means of optimal sets of amplitude gain factors that can be implemented at each single sensor location, while minimizing cross-channel effects that can either degrade the original SQ condition, or even hinder the implementation of independent SQ targets. The proposed framework is verified experimentally, with realistic stationary hybrid electric powertrain noise, showing SQ enhancement for multiple locations within a scaled vehicle mock-up. The results show total success rates in excess of 90%, which indicate that the proposed method is promising, not only for the improvement of the SQ of HEV noise, but also for a variety of periodic disturbances with similar features.

1. Introduction

Economical and environmental aspects compel the automotive industry to make a turn towards eco-friendly and sustainable machine and system design [1–8]. In this direction, the possibility of electrifying vehicle powertrains has become one of

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the main subjects of research in the industry, on the basis that the electric motor (EM), which arguably exhibits better performance than the internal-combustion engine (ICE), is a cleaner source of motive power [2,6,9–12]. Attributes, such as its high performance, still at low rotation speeds, its zero emission operation, as well as its reduced manufacturing costs, make the EM the preferred choice among the available propulsion technologies. However, since the duration of power supply for EMs is currently seen not to endure long journeys, diverse levels of powertrain electrification have been proposed [1,6,13–16]. While the electric vehicle (EV) is intended for short trips, e.g. operation in cities, the HEV benefits from integrating ICEs to its powertrain for extending its autonomy. Even so, in spite of the cost of HEVs as compared to standard ICE cars [1,9,13], they did have succeeded in positioning themselves as the preferred customer choice amongst electrified cars [12,17]. The extended autonomy is mostly acknowledged [5], while still relying on the use of clean sources that provide motive power [11].

Vehicles with hybrid powertrains typically comprise of an important number of parts that operate in different modes, which depend on the current rotation speed, load, breaking and/or recharging regimes [6,13,18]. Some operation modes even demand the parts to co-operate amongst them [19,20]. As one would intuitively reason, the interaction amongst those subsystems results in sounds that are substantially different from that of the ICE itself [20,21]. In particular, the power inverter, which is the part that commands the speed regime of the EM, generates new audible components that are multiples of the switching frequency of the driver. The presence of new audible components in the noise will arguably elicit other than the impressions ICE-propelled vehicles typically evoke [14]. For the ICE-propelled vehicle user who is willing to take a step towards HEVs, it will not be an easy auditory experience to get used to the fact of having such a large amount of harmonics. Another novel but unexpected HEV sound feature is the fact that the spectral lines in the auditory stimulus spread in a larger bandwidth [1]. These NVH aspects may prevent HEVs to be more accepted by customers [8], even when its environmental features are proven to be better than the ones of the ICE-propelled vehicle.

The relationship between the physical parameters of technical sounds and the auditory perception is also currently one of the spotlights of the automotive industry [22]. The possibility for tailoring the residual powertrain noise to provide the driver and passengers with relevant auditory information on the operation regime of the vehicle [23–27], or even for enhancing customer perceptions [28,29] of, e.g. vehicle quality, powerfulness, sportiveness, luxury, reliability quietness, among others [30], also enables the manufacturers to boost their products with unique and distinctive sound marks [31–36]. At that point, SQ techniques come in handy for supporting auditory-oriented procedures, since they bridge the gap between objective vibro-acoustics and the human auditory response, by means of models that quantify auditory perceptions. Whereas it is still possible to cope with the unusual amount of harmonics and spectral crossings amongst them in the hybrid electric powertrain noise, by simply following SQ techniques applied for ICE noise, the fact that its spectrum spreads over a wider bandwidth, sometimes in excess of 4 kHz, does demand the inclusion of more auditory dimensions to the problem, namely other than the widely used low-frequency Loudness [28,34,36–43] and Roughness [28,34–39,42,44–46]. In fact, some recent works on NVH aspects of HEVs [1,6,47] put forward the need for developing SQ approaches that face tonal, narrowband and sharp sounds, which are the novel high-frequency occurrences in the noise that come with integration of the EM in the powertrain. Then, high-frequency SQ metrics, namely Sharpness [20,28,34,37,38,40,42] and Tonality [20,28,41,46,48], should be accounted for when objectively diagnosing -and controlling- the SQ of hybrid electric powertrain noise.

In this line of thought, this paper presents a framework to enhance the auditory perception of the hybrid electric powertrain noise, which copes with the possibility of adapting a sound field towards concurrently optimal SQ targets to each of the four auditory dimensions associated to the sort of noises of concern: Loudness, Roughness, Sharpness and Tonality. In particular, the noise emitted by hybrid electric powertrains, which is structure borne and measured at a number of relevant locations in the vehicle cabin, is tackled through an innovative multichannel distributed algorithm that delivers independent-zone active sound profiling [49]. Contrary to current active noise equalization (ANE) [24,25,27–29] and active sound quality control (ASQC) strategies [26,32,33,36,39,50,51], where the improvement of the soundscape comes as a mere effect of applying a few operation modes, e.g. cancellation, reduction, or amplification, the proposed methodology features a multi-objective optimization stage, which provides the NVH specialist with a variety of optimal solutions, given in terms of amplitude levels that should be attained in the sound, so as to provide the passengers with the exact, desired SQ levels. In this form, amplitude gains of ANE/ASQC schemes in between the widely used 0.0–2.0, which correspond to the cancellation and amplification operation modes, respectively, including the so-called *preservation*, or inactive mode, i.e. $g = 1.0$, become relevant in the proposed framework.

In general terms, the proposed framework for the SQ enhancement of hybrid electric powertrain noise involves four key steps: (i) the diagnosis of the SQ, as measured in the passengers compartment; (ii) the search for enhanced conditions for the sound; (iii) the real-time implementation of the SQ targets via SISO/MIMO active sound quality control schemes; and (iv) the assessment of the controlled sound, in order to verify whether the implemented control tasks did effectively improve its qualities, as prescribed in the optimization stage. The effectiveness of the proposed framework is experimentally demonstrated in a 1:3-scaled vehicle mock-up, instrumented with four sensor/actuator pairs (SAPs) at locations that emulate driver, co-driver and rear passengers. A stationary periodic sound, whose time-frequency pattern has been extracted from a real hybrid electric powertrain emission, is used to excite the mock-up, while ten different optimal solutions have been tested on the sound, for each of the four targeted locations. The controlled sound is eventually assessed with time-domain SQ models, which enables the comparison between optimized and attained SQ scores. Mean success rates obtained from comparing optimized and attained SQ scores above 90% demonstrate the validity of the proposed methodology.