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A multi-harmonic amplitude and relative-phase controller for active sound quality control

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ABSTRACT

Current active sound quality control systems aim at dealing with the amplitude level of the primary disturbance, *e.g.* sound pressure, forces, velocities and/or accelerations, which implicitly leads to Loudness control, regardless of the spectral structure of the disturbance. As far as multi-harmonic disturbances are concerned, auditory Roughness, arguably the most related psychoacoustic metric with rumbling perception in passenger cars, can be tackled not merely by dealing with magnitudes but also with the relative-phase of the narrowband components. This paper presents an adaptive control scheme conceived for dealing with multi-harmonic disturbances, which features the independent amplitude and/or relative-phase control of the input periodic components and an improved robustness to impulsive events. The adaptive control scheme is based on a frequency-domain delayless implementation of the complex-domain, least mean squares algorithm, whereof its convergence process is improved by using a forgetting factor. The control capabilities are evaluated numerically for single- and multiple-harmonic disturbances, including realistic internal combustion engine sound contaminated with noise and by impulsive events. By using long transfer paths obtained from a real vehicle mock-up, sound pressure level reductions of 39 dBSPL and the ability to displacing the relative-phase of a number of narrowband components between $[-\pi, \pi]$ are accomplished by the proposed control scheme. The assessment of the results by using Zwicker-Loudness and auditory Roughness models shows that the proposed adaptive algorithm is able to accomplish and stably preserve various sound quality targets, after completion of the robust convergence procedure, regardless of impulsive events that can occur during the system operation.

1. Introduction

Current active noise control and active noise equalizer systems are proposed to tackle amplitude-level problems, without regarding the spectral nature of the disturbance [1–12]. Even if the incoming signal is broadband or narrowband, the main control target is to deal with its amplitude. Loudness requirements, as the most related psychoacoustic metric with the magnitude of the sound/vibration [13,14], can be met by reducing or, rather equalizing a number of spectral components of the disturbance.

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Concerning the sound quality in passenger vehicles, engine sounds, rather than providing essential information that enables the driver to assess the overall vehicle behavior [13,15,16], are used to reinforce the acoustics of the car and, to a certain extend, of the manufacturer, which results profitable in aid of a *sound branding* design [16,17]. In this regard, engine sounds can be analyzed by taking Loudness as the main psychoacoustic descriptor, followed by the assessment of other related metrics such as auditory Roughness which also plays an important role in defining the overall engine sound quality (SQ) perception [2,13,14,18,19].

Auditory Roughness has been shown as a well-correlated psychoacoustic descriptor for engine sound [2,13,14,16,19–21], since the modulations produced by the interaction of the engine order's amplitude and/or relative-phase relations, mathematically described as a sum of narrowband components related to the engine speed [18,22, Chapter 3]:

$$d[n] = \sum_{k=1}^{O} a_k[n] e^{-j(\omega_k[n] + \theta_k[n])}, \quad k = [1, 2, \ldots, O], \tag{1}$$

induce the passengers a subjective perception commonly qualified as *rumble* [18], *muddy* [23] and/or *annoying* [20].

From psychoacoustics literature, it is a known fact that the auditory Roughness results from the interaction among three nearby harmonic components [18,20,21]. Current narrowband harmonic control schemes can be successfully arranged in parallel by using the common-error approach [6], to deal with the phenomena by controlling their amplitudes [1,5,16,24], on the basis that the linear principle of superposition allows us to arrange as many in-parallel schemes as it will be necessary [5]. However, Zwicker and Fastl's [25] auditory Roughness model, subsequently confirmed by Pressnitzer and McAdams [26], shows that not only the amplitudes, but also the relative-phase of the responsible harmonic components have to be taken into account, if *rumbling* or *Roughness* is settled as a sound quality target [27].

Since the auditory Roughness can also be controlled by dealing with the relative-phases of the components, without altering their amplitudes [16,27], a novel strategy for performing active control other than the classical generation of the counterphase signal for cancelling the incoming signal is presented through this paper, which expands the possibilities regarding the sound quality of a multi-harmonic disturbance. Beside *classical* active sound-profiling [5], which attempts to improve sound quality by merely equalizing the amplitudes of the harmonic components, this paper presents a new possibility of obtaining sound quality targets based on *shiftings* of the relative-phase of the narrowband components in the aforementioned kind of disturbances.

The proposed algorithm consists of a complex-domain version of the simplified-form Fx-LMS [7] and a frequency-domain control updating scheme, which allows direct relationship with psychoacoustic analyses in terms of the responsible narrowband components requiring control and estimation of the parameters of the disturbance. Reduction of the computational burden is achieved by using a frequency-domain, filterbank approach [28] and a delayless structure [10]. Also, improvement of the stability of the updating algorithm facing to impulsive disturbances is attained by using a forgetting factor that weights the recent complex-domain data.

This paper is organized as follows: Section 2 is devoted to present the algorithm. The complex-domain version of the Sun and Meng [7] SF-FxLMS is derived in Section 3, together with some comments about the convergence and the computational complexity of the algorithm. The proposed controller is extensively simulated through a case study with synthesized engine sounds and transfer paths obtained from a real cavity, aiming to demonstrate features such as the independent control of both amplitude and relative-phase of the integer/half-integer engine orders, convergence speed and stability of the system. These results are presented in Section 4. Also, a correlation between the controller results and the final perception of the disturbance, by means of Zwicker-Loudness and auditory Roughness is established. Conclusions are stated in Section 5. All the acoustic quantities are given in dBSPL, *i.e.*1 dB re 20 μPa.

2. An active multi-harmonic amplitude/relative-phase controller for SQ

Tailoring of multi-harmonic disturbances according to sound quality metrics is settled as the main objective of the control actions. SQ numerical analyses over disturbances such as defined in Eq. (1) provide a number of harmonic components requiring control, thus the control actions are redirected to achieve prescribed amplitude levels and/or relative-phase delays/advances, aiming to attain a desired SQ target.

Fig. 1(a) presents the proposed control system, namely the *SF-cFxLMS* algorithm (an acronym for *simplified-form complex FxLMS*). Through this section, we develop various proposed calculations for achieving amplitude and relative-phase control over the aforementioned harmonic components of the incoming sound. The control algorithm comprises two stages: a frequency-domain analysis and updating stage and a time-domain control stage, which constitutes a delayless control structure, according to Kuo et al. [10]. In the frequency domain stage, the algorithm performs an amplitude and relative-phase analysis of the primary disturbance, according to the proposed scheme shown in Fig. 1(b).

Since the disturbance $d[n]$ is not directly accessible by the control algorithm, the algorithm must produce its estimate $\widehat{d}[n]$. A strategy based on an *internal-model* control algorithm [5,29] allows us to define the error signal $e[n]$ as follows:

$$\begin{aligned} e[n] &= d[n] - y[n] \\ &= d[n] - S(z)(w_{l+1}^T[n] x_N[n]), \end{aligned} \tag{2}$$