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Technical note

Active broadband sound quality control algorithm with accurate predefined sound pressure level

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ABSTRACT

The aim of conventional active noise control (ANC) system is to attenuate the sound pressure level (SPL) of unwanted noise as much as possible. However, it is desirable to retain some of the sound with a specified spectrum to meet the requirements of human perception in various applications. This is particularly true in automotive vehicle applications in which some engine noise is to be retained. An active noise equalizer (ANE) is proposed to meet this requirement. This paper proposes an active broadband sound quality control algorithm, based on traditional broadband ANE. The algorithm can not only shape the spectrum of the residual noise according to the sound quality filter, but also control the SPL of the residual noise to satisfy a predefined target accurately, when the amplitude of the disturbance noise changes. This aim is accomplished by introducing a gain factor which is adaptively determined based on the power of the instantaneous disturbance noise and the predefined target. This algorithm has four control modes according to the value of the gain factor. Simulations are carried out to validate the performance of the proposed algorithm using both simulated noise and real vehicle cabin noise. Simulation results show that the SPL error of the proposed control algorithm is within ±2 dB of the predetermined target in the majority of cases simulated. The tracking capability of the proposed algorithm is shown to exhibit good performance in the presence of a time varying SPL target and time varying disturbance noise.

1. Introduction

The active noise control (ANC) system [1–3], based on the principle of acoustic superposition of the original noise and the introduced source generated by a controllable secondary actuator, e.g., loud speaker, provides a suitable method to control low frequency noise, typically below about 500 Hz [4]. ANC techniques have been successfully used in many applications [5–9] since it was proposed by Lueg in 1936 [10].

The aim of traditional ANC systems is to attenuate the residual noise as much as possible. However, in some applications in which human perception is considered, it is desirable to retain some sound with a specified spectrum. For example, a vehicle driver may prefer to hear vehicle and engine sound to enhance the driving experience as well as drive the vehicle safely. To improve the human perception of sound, Sommerfeldt et al. introduced loudness in active noise control [11]. Kuo et al. proposed the adaptive noise equalizer (ANE) algorithm for narrowband noise [12,13], which can either amplify or attenuate sinusoidal noise by a predetermined amount. Gonzalez et al. extended ANE to the multichannel case [14]. The concept of ANE was extended to broadband noise in [15]. On the basis of narrowband ANE, Kuo et al. [16] proposed the concept of active sound quality control (ASQC). The ASQC concept was extended to broadband noise using a frequency domain delay-less sub-band filtered-x least mean square (FxLMS) algorithm [17]. The broadband ASQC algorithm can shape the spectrum of the residual noise with a predetermined sound quality filter. The ASQC algorithm is the combination of ANC and psychoacoustics [18], an area that investigates the perception of the sound. However, as is analyzed in [19,20], neither the traditional narrowband nor broadband ASQC algorithm is practical when the sound pressure level (SPL) range of the disturbance noise is broad. As is discussed in [20], the traditional ASQC algorithm shifts the disturbance noise in an SPL range of [*A*, *B*] dB to a residual noise with an SPL range of [*A*-*R*, *B*-*R*] dB linearly, where *A* and *B* are the lower and upper bound of the original disturbance noise SPL, respectively, *R* is the reduction amount of the ASQC algorithm, *A*-*R* and *B*-*R* are the lower bound and upper bound of the residual noise SPL following the convergence of the ASQC controller, respectively. Hence, the SPL range of the residual noise is $(B - A)$ dB, which is the same as that of the original disturbance noise.

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The objective of this work is to modify the SPL by decreasing large amplitude SPL as required within some spectrum, and increasing small amplitude SPL where required in the remaining spectrum. To solve this problem, Feng et al. proposed an adaptive active noise equalizer [19] for narrowband noise spectrum shaping, and a self-tuning active noise equalizer [20] for broadband noise spectrum shaping. The broadband self-tuning ANE algorithm compresses the SPL of the disturbance noise to a relatively narrow range by introducing a nonlinear adjustable gain factor to the traditional broadband ANE. However, in some application, it is required to control the SPL of the residual noise to a predefined target with specified spectrum rather than a SPL range. For example, when designing an automobile, it is desirable for the interior SPL of the vehicle cabin to increase linearly with the vehicle speed [21,22]. If passive methods such as structural modification are used to solve the deviation of SPL from linearity over some vehicle speed range, they often require many design iterations in order to fulfill the desired SPL target, leading to a costly design process. In addition, passive solutions may affect the sound in other speed. Moreover, passive approaches to change the SPL over a specific frequency range may increase the weight of the vehicle and result in low fuel efficiency.

This paper introduces a new adaptive gain factor which is adjusted adaptively according to the predefined SPL target and the disturbance noise power to meet the above requirements. Further, the proposed algorithm exhibits the spectrum shaping properties of the traditional broadband ANE.

This rest of this paper is organized as follows: Section 2 provides a derivation of the proposed active broadband sound quality control algorithm. In Section 3, simulation results configured with simulated reference noise and vehicle cabin noise are presented to validate the performance of the proposed algorithm. Conclusions are given in Section 4.

2. Proposed algorithm

The broadband self-tuning ANE algorithm proposed by Feng and Gan [20] on the basis of broadband ANE [15] is shown in Fig. 1, with all terms defined in the figure. In their work, the authors introduced a nonlinear adaptive gain factor $\alpha(n)$, highlighted by the dashed box in Fig. 1, to compress the SPL of the disturbance noise to a bandlimited range. For an ideal case where $S(z) = \widehat{S}(z)$, the residual noise following convergence of the self-tuning ANE can be expressed as:

$$e(n) = \alpha(n) \cdot c(n) * p(n) * x(n) = \alpha(n) \cdot c(n) * d(n) \tag{1}$$

where $e(n)$ is the residual noise following convergence of the controller, $c(n)$ is the impulse response of the sound quality filter, the length of $c(n)$ is L, $p(n)$ is the impulse response of the primary path, $x(n)$ is the reference noise, $d(n)$ is the disturbance noise, $*$ denotes linear convolution. While this enhancement to the broadband ANE [15] made the broadband ANE more suitable for practical use. However, in some applications, as discussed in the introduction, the SPL of the residual noise must be controlled to a predefined value over a pre-specified spectrum, hence this algorithm is ineffective. Here, we propose to use a new adaptive gain factor with the self-tuning ANE algorithm to achieve this objective.The proposed broadband ASQC algorithm is extended based on self-tuning ANE proposed by Feng and Gan [20]. The schematic diagram of the proposed algorithm is identical to the self-tuning ANE algorithm, shown in Fig. 1. To control the SPL of the residual noise to predefined values over a specified spectrum, we introduce an adaptive gain factor, denoted as $k(n)$. In the following section the expression for the adaptive gain factor $k(n)$ is derived.

As can be seen from Eq. (1), the residual noise, following convergence of the controller, can be written as:

$$e(n) = k(n) \cdot \sum_{l=0}^{L-1} c(l) d(n-l) \tag{2}$$

The deviation below is based on the work of [23,24]. The autocorrelation function of the residual noise $e(n)$ can be expressed as:

$$\begin{aligned} R_{ee}(n, n+m) &= E[e(n) \cdot e(n+m)] \\ &= E[k(n) \cdot c(n) * d(n) \cdot k(n+m) \cdot c(n+m) * d(n+m)] \end{aligned} \tag{3}$$

where m is the time delay, $E[\cdot]$ denotes mathematical expectation. Assuming that $k(n)$ changes slowly, therefore, $k(n) \approx k(n+m)$, we can write:

$$\begin{aligned} R_{ee}(n, n+m) &= k^2(n) E[c(n) * d(n) \cdot c(n+m) * d(n+m)] \\ &= k^2(n) E\left[\sum_{l=0}^{L-1} c(l) d(n-l) \sum_{\mu=0}^{L-1} c(\mu)(d(n+m-\mu))\right] \\ &= k^2(n) E\left[\sum_{l=0}^{L-1}\sum_{\mu=0}^{L-1} c(l) c(\mu) d(n-l) d(n+m-\mu)\right] \end{aligned} \tag{4}$$

Since the coefficients $c(l)$ and $c(\mu)$ are fixed for all $l$and μ, Eq. (4) can be rewritten as:

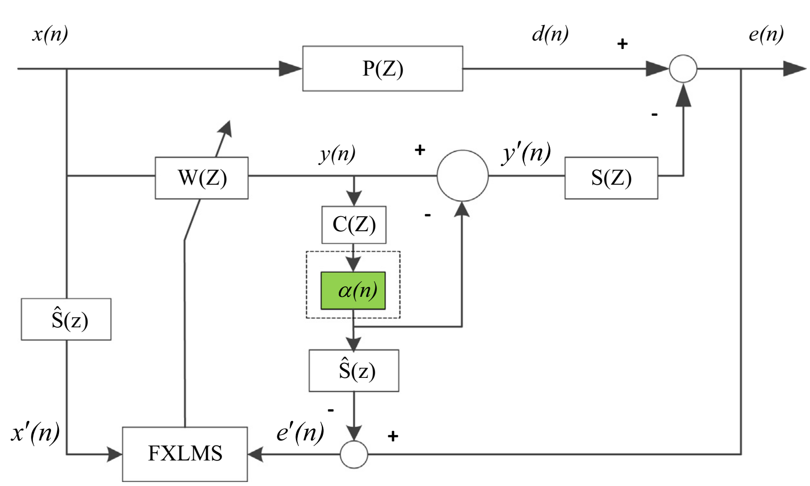

Fig. 1. Block diagram of broadband self-tuning ANE system proposed in [20] ($x(n)$: reference noise, $P(z)$: primary path, $d(n)$: disturbance noise, $e(n)$: residual noise, $W(z)$: adaptive filter, $y(n)$: output of the adaptive filter, $y'(n)$: cancelling signal, $S(z)$: secondary path, $S'(z)$: estimated secondary path $C(z)$: sound quality filter, $x'(n)$: filtered reference noise, $e'(n)$: pseudo residual signal).