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Redundancy-Aware Reference Signal Selection for Automotive Active Road Noise Control

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Abstract

This paper proposes a strategy for an FxLMS-based automotive active road noise control (ARNC) that accounts for redundancy among reference signals and is intended for automotive ARNC systems with limited computational resources. Usually, multiple reference signals of vehicles with ARNC systems are measured by accelerometers mounted at each wheel hub. However, due to the structural characteristics of vehicles, these reference signals are often strongly correlated with each other, and the increased number of references does not necessarily yield proportional improvements in noise attenuation performance, while raising computational load as well as requiring additional memory resources. The proposed method evaluates independent contribution of each candidate reference signal across the operating frequency band and progressively ranks reference signals based on their relevance to the error signal and their independent contribution beyond the selected subset among all reference signals, while excluding reference signal channels whose contribution is already explained by the selected subset, which are redundant signals. Real-vehicle experiments demonstrate that acceptable noise attenuation performance is maintained with a reduced number of reference signals, while reducing computational load and filter memory requirements.

Keywords: *FxLMS, active road noise control, reference signal selection, computational efficiency*

1. Introduction

Interior quietness is a key factor in determining ride comfort and vehicle quality [1]. With the increasing adoption of electric vehicles, low-frequency interior noise has become increasingly important. Road noise generated by tire-road interaction significantly affects the low- and mid-frequency ranges, where passive methods are less effective. Active road noise control (ARNC) has therefore gained attention as an effective alternative [1-4].

Feedforward ARNC systems commonly employ the filtered-x least mean square (FxLMS) algorithm, and their achievable control performance depends strongly on the coherence between the reference and error signals [2,5]. In general, increasing the number of reference signals can improve multiple coherence and noise suppression performance. However, when additional channels contain redundant information, the resulting performance improvement may be limited, while the required number of adaptive filters, memory usage, and computational burden increase [5,6]. In software-defined vehicle (SDV) architectures, where multiple functions are integrated into a single system-on-chip (SoC), reducing redundant reference channels while maintaining control performance is particularly important.

Previous studies have reduced the reference dimension by synthesizing orthogonalized virtual reference signals [6,7] or selected an optimal sensor configuration from a larger set of candidate locations [8]. In contrast, the present study determines a practical reduction order for physical reference channels already installed in a vehicle.

This study determines the reduction order of pre-installed reference channels by combining coherence-based relevance to the error signal with conditional residual-based measures of independent contribution. Candidate channels are evaluated based on both their ability to explain the error signal and the additional information they provide beyond the selected reference set, enabling the identification and removal of redundant channels while retaining those that substantially contribute to control. The proposed reduction procedure is validated by analyzing performance degradation during channel removal. Vehicle tests demonstrate that removing low-contribution channels first reduces computational and memory requirements with less performance degradation than removing high-contribution channels.

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2. Methodology

2.1 Control algorithm

In this study, Modified FxLMS was used for adaptive control of vehicle interior noise. Accelerometers mounted near the four-wheel hubs served as reference inputs, interior microphones as error inputs, and vehicle audio speakers as control outputs. The algorithm generates control signals predicted from the references and updates the adaptive filter coefficients to minimize the residual error after the control sound propagates through the secondary paths [1,2].

2.2 Reference selection

Reference selection is performed offline to identify channels that provide new information within the pre-installed reference set. Each candidate is evaluated based on its error prediction capability and redundancy with the selected references. Rather than directly applying backward elimination, relative channel importance is ranked through greedy forward selection, and the reverse ranking is used as the channel reduction order.

First, the auto- and cross-spectra of the reference and error signals are estimated using Welch's method [9]. Let X and E denote the reference set and error signal, respectively. At each frequency bin f, the reference spectral matrix $G_{XX}(f)$, reference-error cross-spectral vector $G_{XE}(f)$, and error autospectrum $G_{EE}(f)$ are calculated. Following Bendat and Piersol [10], the multiple coherence between error channel e and selected reference subset S is defined as follows.

$$\gamma_M^2(S,e;f) = \frac{G_{XE,S}^H(f)\left(G_{XX,S}^{reg}(f)\right)^{-1} G_{XE,S}(f)}{G_{EE}(f)} \qquad (1)$$

$G_{XX,S}(f)$ is the spectral submatrix corresponding to the selected reference subset, and $G_{XE,S}(f)$ is the cross-spectral vector between the selected references and the error signal. To mitigate numerical instability caused by high correlation among the reference signals, Tikhonov regularization is applied as follows [11].

$$G_{XX,S}^{reg}(f) = G_{XX,S}(f) + \alpha \frac{\mathrm{tr}\left(G_{XX,S}(f)\right)}{|S|} I \qquad (2)$$

α is the regularization coefficient and is set to 0.05. Redundancy between a candidate reference channel and the selected reference set is evaluated using the Schur complement-based conditional residual power. Given the selected set S and candidate j, the conditional residual power of j is defined as follows.

$$SC_{j|S}(f) = G_{XX}(f,j,j) - G_{XX}(f,j,S)\left(G_{XX,S}^{reg}(f)\right)^{-1} G_{XX}(f,S,j) \qquad (3)$$

By normalizing it with the candidate reference auto spectrum, the band-averaged independent contribution, ΔJ_j, is defined as follows.

$$\Delta J_j = \frac{1}{B}\sum_{f\in B} \min\left[1, \max\left(0, \frac{SC_{j|S}(f)}{G_{XX}(f,j,j)}\right)\right] \qquad (4)$$

Here, B denotes the set of frequency bins within the evaluation band. A ΔJ_j value near 1 indicates that the candidate contains substantial information unexplained by the selected references, whereas a value near 0 indicates high redundancy [12]. However, as high independent contribution does not necessarily imply strong error predictability, the increase in multiple coherence is also considered.

Reference channels are selected sequentially using greedy forward selection. The band-averaged single coherence is first calculated for each channel, and the channel with the highest value is selected as the initial seed . For each remaining candidate j, the independent contribution $\Delta J_j$and the increase in multiple coherence are then calculated.

$$\Delta\gamma_M^2(j) = \bar{\gamma}_M^2(S \cup \{j\}) - \bar{\gamma}_M^2(S) \qquad (5)$$

$\bar{\gamma}_M^2$ denotes the band-averaged multiple coherence. At each iteration, only candidates with ΔJ_j above the specified threshold is retained, and the channel with the largest $\Delta\gamma_M^2(j)$is added to the selected set. Selection terminates when no candidate satisfies the independent contribution threshold or when the maximum multiple coherence increases falls below the stopping criterion. This process selects reference channels by considering both error predictability and redundancy among the selected references.

3. Experiments and Results

3.1 Test condition

The proposed reference channel selection method was validated using data acquired from electric vehicle. The driver and front passenger seats were selected as control positions, with two error microphones installed at each seat, as shown in Figure 1. Reference signals were measured using triaxial accelerometers mounted near the four-wheel hubs at production locations. Control signals were generated through eight vehicle audio speakers. Driving tests were conducted at 40 km/h on the noise test track at the Hyundai Mobis Seosan Proving Ground. The control frequency range was 10–400 Hz.

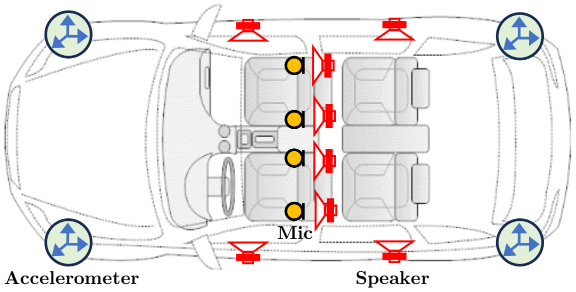

Figure 1. Sensor and speaker configuration of test vehicle

3.2 Reference selection result

First, the band-averaged single coherence over the control frequency range was calculated for each reference channel and used to select the initial seed for greedy selection. As shown in Table 1, Ref. 07 had the highest coherence among the 12 channels and was therefore selected as the initial seed.

Table 1. Table captions should be placed above the table.

Ref. index	Coherence (γ^2)
Ref 00	0.1776
Ref 01	0.1769
Ref 02	0.1239
Ref 03	0.1486
Ref 04	0.2192
Ref 05	0.1447
Ref 06	0.1916
Ref 07	0.2943
Ref 08	0.1454
Ref 09	0.2058
Ref 10	0.1643
Ref 11	0.1055

Using stopping criteria of 5% for independent contribution and 0.03 for multiple coherence increase, Ref. 07, 03, 09, 04, 10, 01, 06, and 11 were selected sequentially. To validate the effectiveness of the proposed ranking for channel reduction, the greedy expansion was continued for the remaining channels without the independent contribution stopping criterion, yielding a complete ranking of all 12 reference channels. The final importance ranking was Ref. 07, 03, 09, 04, 10, 01, 06, 11, 02, 08, 00, and 05. The channels were then removed sequentially from the lowest-ranked channel, and the resulting degradation in vehicle ANC performance was analyzed.

Table 2. Performance degradation with low-contribution channel removal.

Number of Active reference channels	Removed Reference Channels	Performance Degradation (dB(A))
12	None (Baseline)	0.00
11	Ref 05	-0.12
10	Ref 00, 05	-0.34
9	Ref 00, 05, 08	-0.45
8	Ref 00, 02, 05, 08	-0.69
7	Ref 00, 02, 05, 08, 11	-1.14
6	Ref 00, 02, 05, 06, 08, 11	-1.49

As shown in Table 2, removing one or two low-contribution channels limits performance degradation to 0.12 dB(A) and 0.34dB(A), respectively. Performance gradually decreases as more channels are removed, reaching a 1.49 dB(A) loss when six channels remain.

These results show that lower-ranked channels contribute relatively little. However, the marked degradation at six channels indicates that not all lower-ranked channels can be removed. In practice, the number of active reference channels should be determined by balancing acceptable performance degradation against resource savings.

To validate the effectiveness of the proposed ranking criterion for channel reduction, a reverse removal test is conducted. High-contribution channels selected earlier by the greedy algorithm are removed sequentially in the order Ref. 07, 03, 09, 04, 10, and 01.

Table 3. Performance degradation with high-contribution channel removal.

Number of Active reference channels	Removed Reference Channels	Performance Degradation (dB(A))
12	None (Baseline)	0.00
11	Ref 07	-0.14
10	Ref 03, 07	-0.25
9	Ref 03, 07, 09	-0.72
8	Ref 03, 04, 07, 09	-1.19
7	Ref 03, 04, 07, 09, 10	-1.48
6	Ref 01, 03, 04, 07, 09, 10	-1.78

Removal of high-contribution channels shows a different trend from removal of low-contribution channels. With nine channels, removing high-contribution channels causes a 0.72dB(A) performance loss, compared with 0.45dB(A) for low-contribution channel removal. With eight channels, the losses are 1.19dB(A) and 0.69dB(A), respectively. When reduced to six channels, removing high-contribution channels increases the performance loss to 1.78dB(A).

This counter-validation confirms that the proposed ranking method effectively identifies high-contribution and redundant reference channels. Consequently, removing lower-ranked channels first minimizes ANC performance degradation during channel reduction, providing a practical basis for reducing sensor count under resource constraints.

Reducing the number of reference channels decreases both the reference paths and adaptive filters in the FxLMS algorithm. As shown in Fig. 2, the computational load and filter memory requirement decrease linearly with the number of reference channels. Under the controller and algorithm configuration used in this study, each removed reference channel reduces the computational load by approximately 5.1% and the filter memory requirement by 8.33% relative to the 12-channel configuration.

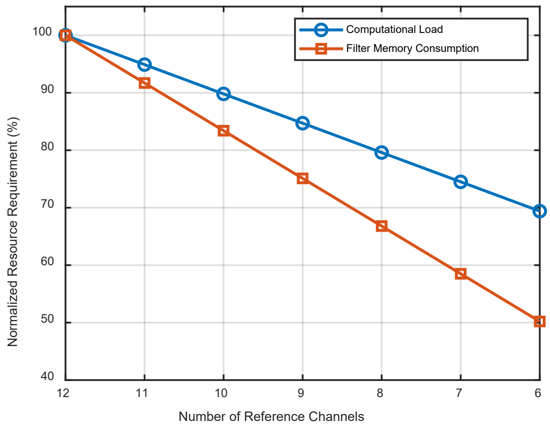

Figure 2. Normalized computational load and filter memory consumption requirement as a function of the number of reference channels.

These results demonstrate that reference channel reduction can significantly decrease the computational and memory requirements of real-time ANC controllers while maintaining acceptable control performance. In the 8-channel configuration, the computational load and filter memory requirement were reduced by 20.4% and 33.2%, respectively, compared with the 12-channel baseline, with only a 0.69 dB(A) degradation in noise reduction performance.

The eight-channel configuration therefore represents a practical trade-off between control performance and resource savings. However, this study does not define a single optimal channel count. The appropriate operating point depends on the acceptable performance loss and the computational and memory constraints of the target controller. The key result is that the proposed selection criterion achieves resource savings with less performance degradation than arbitrary channel reduction.

4. Conclusion

This study applies an existing greedy reference selection method to rank pre-installed reference sensors and determine the channel reduction order. Vehicle tests show that removing low-contribution channels causes less performance degradation than removing high-contribution channels at the same channel count. In the eight-channel configuration, the respective performance losses are 0.69dB(A) and 1.19dB(A), confirming that the ranking reflects each channel's contribution to ANC performance. These results demonstrate that, under the tested conditions, the proposed ranking provides an effective basis for determining the channel reduction order while balancing performance degradation and resource savings in production systems.

The present study is validated using data from a single vehicle under a specific operating condition. Therefore, the optimal channel reduction order may vary depending on vehicle platform, sensor configuration, and driving conditions. Future work will investigate the robustness of the proposed ranking method across different vehicle models and operating environments and establish practical guidelines for channel reduction in production ARNC systems.

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