

Research Progress on Active Control of Road Noise in Vehicles

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Abstract— In recent years, active control of road noise (RNC) attracts significant attention because road noise generated by the interaction between tires and the pavement has become a dominant noise source in vehicles during daily driving, especially for electric vehicles. Although RNC has been under development for over three decades since 1994, its performance still has some gaps to people's expectations in applications. Challenges exist in several aspects, such as noise reduction levels, robustness, and system complexity, which require further investigation. In this paper, the research history of RNC is reviewed briefly first, then recent research progress made by Nanjing University is reported. Finally, challenges and future research directions are discussed.

I. INTRODUCTION

In recent years, active control of road noise (RNC) has attracted significant attention in electric vehicle industry, as the dominance of tire-pavement interaction noise has become evident in the cabin at speeds below 100 km/h [1]. For instance, Hyundai Motor Group announced the development of the world's first RNC system with a noise reduction of 3 dB [2]. Jaguar Land Rover also unveiled an RNC technology that can reduce the peak noise level by 10 dB and the overall noise level by 3 ~ 4 dB [3]. RNC technology debuted in the Avita 11, which can comprehensively reduce road noise within the frequency range of 40 ~ 500 Hz [4]. The noise level inside the cabin of the newly released Maextro S800 was reduced to 56.7 dBA at 60 km/h on rough roads, leveraging multiple technologies including RNC [5]. Despite the applications of RNC technologies in mass production of several vehicle models, actual subjective noise reduction experience remains insufficiently significant due to its limited noise reduction performance.

The research on RNC was first conducted by the University of Southampton around 1994 [6]. An early experiment was performed on a Citroen AX travelling at 60 km/h on a rough asphalt road, where a low-frequency "rumble" was present in the 100 ~

200 Hz range. Reference signals were acquired using six accelerometers symmetrically mounted on the floor, wishbone, and wheel hub, and two front door loudspeakers were selected as secondary sources. Real-time control results demonstrated that the A-weighted sound pressure level (SPL) was reduced by approximately 7 dB in the 100 ~ 200 Hz range. Over the past three decades, RNC systems have been improved in several aspects, including error signal acquisition, reference signal sensing strategies, algorithm optimization, and system implementation.

The error signals at the human ears are essential for adaptive RNC systems, but direct microphone placement at the ears is impractical. To address this, the remote microphone technique (RMT) was proposed, utilizing pre-trained observation filters to estimate ear-level sound pressure [7]. Since then, RNC systems integrated with RMT have garnered significant academic interest. In an experiment conducted in a large SUV travelling at 80 km/h on a rough road, 16 monitoring microphones were arranged around a dummy head in the right rear seat. Results indicated that using 4 or 16 microphones achieved upper limit frequencies of 400 Hz or 800 Hz, respectively, where the estimation error was less than -10 dB. Offline simulations demonstrated a total A-weighted SPL noise reduction of approximately 3.7 dB in the frequency band below 1000 Hz [8]. Subsequent studies have revealed that RMT is more sensitive to changes in the device response of monitoring microphones than to changes in the reference signal [9].

The number and placement of physical microphones are critical for effective RMT implementation. Coherence-based studies showed that positioning physical microphones within half the wavelength of the target frequency around a virtual microphone maintains a coherence coefficient of at least 0.9 and keeps the virtual error signal estimation error below -10 dB [10]. Moreover, the required spacing between microphones decreases as the sound source approaches the microphones [11]. A double-layer arrangement of physical microphones can further reduce

estimation errors by capturing sound pressure gradient information [12]. However, RMT relies on a stable sound field and extensive pre-training, posing challenges in practical applications due to the substantial workload associated with training and storage requirements.

Feedforward control systems are widely used in RNC due to their control robustness, and the quality of reference signals determines the upper limit of noise reduction performance. Accelerometers are commonly chosen as the reference sensors and installed at powertrain mounting points, suspension hard points, and body structure support points because road noise below 500 Hz is primarily transmitted into the cabin through structural paths [13]. Frequency-domain unconstrained optimization has shown that the optimal number of reference sensors is determined by the number of significant excitation sources [14].

In the development of RNC systems, the number of reference sensors has gradually increased. Initially, six accelerometers achieved a noise reduction of 7 dB in the 100 ~ 200 Hz frequency band at a vehicle speed of 60 km/h [6]. Subsequent studies used 18 accelerometers in a mid-size SUV and achieved a broadband noise reduction of approximately 7.6 dB below 500 Hz at 60 km/h [15]. To date, the largest reported configuration includes 12 three-axis accelerometers and 10 single-axis accelerometers (a total of 46 reference signals), which achieved a noise reduction of 9.2 dBA in the 20 ~ 1000 Hz range at a vehicle speed of 50 km/h [16]. To balance noise reduction performance with system complexity, recent studies have optimized the arrangement of reference sensors using methods such as coherence analysis [17], Fisher information matrix [18], and structural transfer path analysis [18], allowing for a reduction in the number of reference signals without compromising noise reduction effectiveness.

To enhance noise reduction performance and reduce complexity of adaptive feedforward RNC systems, several studies have focused on the improvement of adaptive algorithms [19]. For instance, the time-frequency filtered-x least mean square (TF-FxLMS) algorithm updates the control signal in the time domain to ensure real-time performance while computing the filtered reference signal and gradient estimation in the frequency domain to reduce computational load. It reduces the multiplication and addition operation counts to 24% and 27% of those in the conventional FxLMS, respectively [20]. Another example is the online decoupling-whitening frequency-domain filtered-error least mean square (ODW-FDFeLMS) algorithm, which decomposes secondary paths into all-pass and minimum-phase components via inner-outer product factorization to eliminate path cou-

pling, thereby enhancing system convergence speed and reducing computational complexity [21]. In a real-time experiment in an electric vehicle with 12-channel reference signals, this algorithm converged within 15 seconds, and achieved mean noise reductions of 5.1 dBA and 5.0 dBA at the left and right ears, respectively, across the 50 ~ 1500 Hz frequency band. In principle, the noise reduction achieved by the aforementioned adaptive algorithms still falls short of the ideal result of Wiener filtering, leaving room for further improvement.

In addition to feedforward control systems, feedback control systems and feedforward-feedback hybrid control systems have been investigated. Studies have shown that feedback control is sensitive to plant delay [22] and more effective for narrow-band noise control [23]. Under the internal model control (IMC) framework, solving the control filter coefficients through convex optimization algorithms can enhance the system's robustness to occupant changes [24]. A compensation control strategy that utilizes the acoustic field spatial characteristics between the microphone and the human ear to compensate for the microphone signal can achieve a noise reduction of 2.0 dB higher than direct control in the narrow-band frequency range of 170 to 350 Hz [25]. A hybrid system composed of a centralized feedforward subsystem and a distributed feedback substructure has been investigated, and the system parameters were optimized by a non-dominated genetic algorithm. Experimental results show that the hybrid system achieves a noise reduction of 5.9 dB in total SPL within the frequency range of 50 to 250 Hz [26].

The subsequent chapters of this paper introduce recent research progress from three aspects: expanding the noise reduction bandwidth for global control systems, enhancing the noise reduction level for local control systems, and developing the low-complexity adaptive algorithm for multi-reference RNC systems.

II. RECENT PROGRESS

A. Expanding Control Bandwidth for Global RNC Systems

For enclosed spaces with multiple sound sources, such as automotive cabins, the key to achieving global noise reduction lies in the effective suppression of all acoustic modes within the target frequency band [27]. Previous studies selected 4 door speakers as secondary sound sources, which only suppressed a limited number of modes, resulting in an upper limit frequency of approximately 200 Hz for global noise reduction [6]. To improve the global control performance, one solution is to increase the number of secondary sources. The influence of secondary sound source configurations on the upper limit frequency of global noise reduction in car cabins has been investigated [28].

Frequency-domain simulations were conducted based on a finite element model of an enclosure with dimensions of 1.9 m × 1.5 m × 1.1 m and sound-absorbing inner boundaries. A total of 478 uniformly distributed monopole sources with random strengths were set as primary sound sources, and 1536 evaluation points were evenly distributed in the cabin. The simulations showed that when 1, 4, or 16 secondary sound sources were used and the absorption coefficient was set to 0.2, the upper limit frequencies for achieving 3 dB global noise reduction were 160 Hz, 400 Hz, and 840 Hz, respectively. By considering the simulation results under varying sound absorption conditions, a formula was proposed for the upper frequency limit for achieving 3 dB noise reduction in global RNC systems:

$$f_{\max} = \gamma c_0 \sqrt{N/S}. \quad (1)$$

where γ is a constant related to the boundary absorption coefficient, c_0 is the sound speed in air, N is the number of secondary sound sources, and S is the total area of the side walls of the rectangular enclosure.

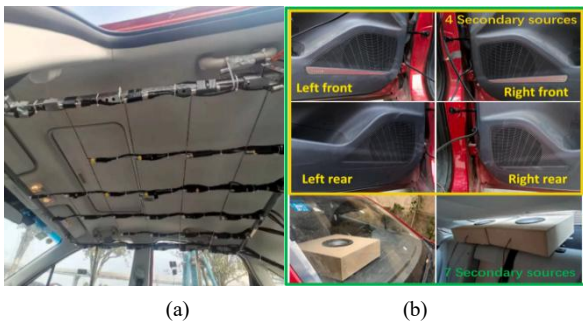


Fig. 1 Layout of in-vehicle system: (a) evaluation point plane; (b) two secondary sound source configurations.

Fig. 1 depicts the experimental setup in an electric vehicle travelling at a constant speed of 50 km/h on an asphalt road. The SPL at 40 evaluation points located on a plane 10 cm below the vehicle ceiling and the vibration reference signals acquired by 16 accelerometers mounted on the vehicle chassis were measured simultaneously. Two configurations of secondary sound sources were investigated: four door speakers and seven speakers (four door speakers plus three additional speakers). The sampling frequency was 4 kHz and the sampling duration was 50 s.

Fig. 2 presents the average SPLs measured at 40 evaluation points in the 1/3 octave bands with and without active noise control. It is observed that when 4 door-type speakers were used as secondary sound sources, the noise reduction exceeded 3 dB in the 1/3 octave bands with a center frequency below 200 Hz. When all 7 secondary sound sources were used, the upper limit frequency for 3 dB effective noise reduction increased to 250 Hz.

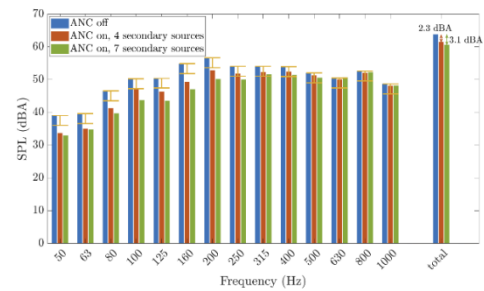


Fig. 2 The average SPLs at the evaluation points in 1/3 octave bands with and without ANC measured in the experiments.

Although the upper limit frequency was increased for global noise reduction with more secondary sources, it should be noted that as the modal density of an enclosure increases with the square of frequency, achieving an upper limit frequency of 1000 Hz for a global noise reduction system would require more than 100 sound sources, according to formula (1). This remains a significant challenge for practical applications.

B. Enhancing Noise Reduction Level for Local RNC Systems

Headrest speakers can be employed as secondary sound sources in local RNC systems due to their simple structure and feasible installation. However, the head movements can lead to significant variations in the response of secondary paths because the distance between headrest speakers and the human ear is close. This can cause substantial degradation in the system noise reduction performance. To address this, a quantitative study was conducted on the noise reduction loss due to head movements in an RNC system with dual secondary speakers installed on the seat shoulders. Results show that the average noise reduction loss caused by head translation and rotation increases with rising frequency, increasing movement distance, and higher initial noise reduction levels. Experiments conducted in an electric vehicle travelling at 50 km/h demonstrate that when the initial noise reduction is approximately 9.2 dBA and the maximum allowable noise reduction loss is 3 dBA, the head translation distance should not exceed 2.0 cm, and the rotation angle should not exceed 6.2 degrees [16].

The performance of RNC systems is affected by human factor parameters. A study was conducted on the impact of actual human postures in three different scenarios, with three scenarios of human posture changes designed: FIX (passengers remaining stationary), MoveIncar (free movement in the vehicle followed by returning to the initial position), and MoveOutside (getting off the vehicle and then returning to the initial position). Ten subjects (5 males and 5 females) with heights ranging from 155 cm to 185 cm were selected to participate in the test. A depth camera was used to track the ear positions, and the secondary paths from two headrest speakers to two microphones fixed at

the ears were measured. To capture the randomness and repeatability of minor head movements, each subject repeated the measurement 5 times in each scenario, establishing the first ANC headrest secondary path database for actual human head movements with 600 entries.

Real-time in-vehicle control experiments were conducted when the electric vehicle was travelling at 50 km/h. Two subjects moved as required in each scenario, with measurements repeated 5 times. The A-weighted total SPL noise reduction within the 100 ~ 2000 Hz frequency range at the left/right ears of different subjects was calculated under various scenarios. Experimental results showed that when the initial noise reduction was constrained to 10.7 dBA, the maximum noise reduction loss was 2.5 dBA after subjects freely moved in the seat and returned to the initial position and posture. By contrast, when subjects got off the vehicle and then attempted to restore the initial position and posture, the maximum noise reduction loss reached 5.8 dBA. This indicates that the impact of occupant posture changes on the noise reduction performance of local RNC systems cannot be ignored [29].

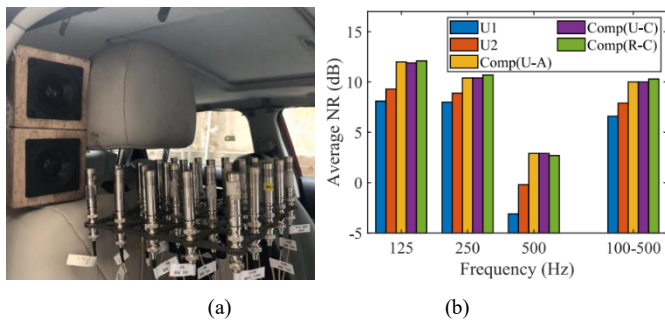


Fig. 3 (a) Photograph of the experimental setup; (b) the average noise reduction in the target area for different types of secondary sources.

To enhance the performance of local RNC systems against human head movement, a composite sound source with uniform near-field radiation characteristics was developed [30]. The composite source was composed of two loudspeaker units arranged vertically at a 10 cm spacing as shown in Fig. 3(a). Its performance was optimized via sound-pressure matching technology. An experiment was conducted in an electric vehicle travelling at speeds of 50 km/h with 25 microphones uniformly distributed across a 20 cm × 20 cm target area at the ear-height plane of the front passenger seat to acquire sound pressure signals. Accelerometers were deployed to collect 44 reference signals from the vehicle chassis. Fig. 3(b) shows the average noise reduction effect of different types of secondary sources at all measurement points in the target area. Here, U1/U2 denote single secondary sources, and U-A/U-C/R-C are three optimization strategies for composite sources, where R-C performs control based on the

measured road noise field and in-vehicle secondary paths. It is demonstrated that noise reduction effect of the composite sources outperforms that of the single units. In the 100 ~ 500 Hz frequency band, compared with U1/U2, the average noise reduction of composite sources was improved by at least 3.0 dB/2.1 dB.

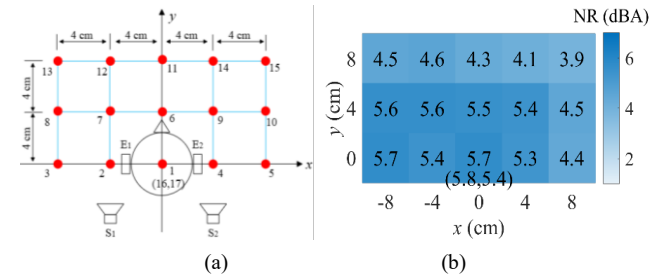


Fig. 4 Head movement within a 16 cm × 8 cm grid: (a) Dot position diagram (b) The noise reduction of the A-weighted overall SPL between 50 and 2000 Hz at the right ear in 20 minutes with regularization

Research has been conducted on an adaptive RNC headrest using RMT, in which two regularization strategies for improving convergence stability were proposed and compared (one for observation filter modeling and the other for adaptive control implementation). Simulation results based on the measured data show that if the modeling accuracy is sufficient, applying regularization in observation filter modeling can achieve better noise reduction. As shown in Fig. 4(a), the initial position of the dummy head's center is labelled as position 1. The head can translate on a 16 cm × 8 cm grid with an interval of 4 cm in the horizontal x-y plane. Position 16 denotes that the head translates downward by 4 cm, while position 17 denotes that the head translates upward by 4 cm. When the head is translated more than 8 cm from the initial position without head tracking, the adaptive ANC headrest is prone to instability due to changes in the observation filter and secondary path. However, the system can maintain stability through appropriate regularization. For example, in Fig. 4(b), when a positive real regularization factor is applied to constrain the observation filter, the noise reduction in a 16 cm × 8 cm area is at least 3.9 dBA.

C. Developing the Low-Complexity Adaptive Algorithm

From the perspective of improving algorithm convergence performance and computational efficiency, the BCD-Newton algorithm (an improved least mean square Newton algorithm based on block coordinate descent) is proposed [31], as shown in Fig. 5. By dividing the control filter into channel-level blocks and updating each block sequentially, the algorithm swaps full large autocorrelation matrix computation and inversion for smaller channel-specific Toeplitz matrices to slash computational loads significantly. This block update approach is also

paired with a data pool mechanism that performs updates per data pool instead of sample-by-sample, which boosts the reliability of correlation estimation. Additionally, a forgetting factor is added to balance the use of historical data and dynamic adaptability, addressing estimation errors in real-time scenarios. Through these designs, the algorithm reduces computational complexity while maintaining the convergence performance of traditional algorithms.

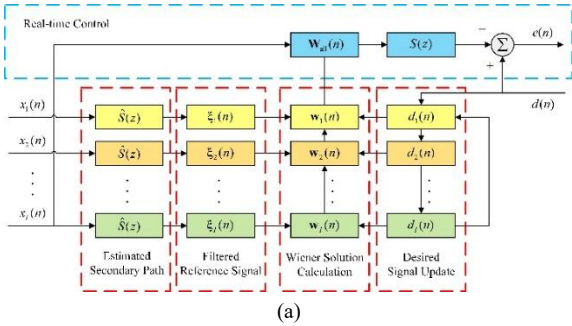


Fig. 5 Block diagram of BCD-Newton algorithm.

Simulations based on measured data show that in an electric vehicle travelling at a constant speed of 50 km/h, the BCD-Newton algorithm converges within 40 s when 42 reference signals are used, while the FxNLMS algorithm does not converge even after 50 s. The average noise reduction at the ears with the proposed BCD-Newton algorithm is 0.5 dBA, which is 3.4 dBA higher than that with the FxNLMS algorithm, and nearly consistent with the result obtained using the traditional LMS-Newton algorithm. The computational complexity of the BCD-Newton algorithm is about 30% of that of the FxNLMS and 2% of that of the LMS-Newton algorithm.

The on-vehicle test data used in the BCD-Newton algorithm research are all from the publicly released dataset^[32]. Interested researchers can download it for free from the following link provided by our group: <https://box.nju.edu.cn/published/rnc-data/>.

III. DISCUSSIONS AND CHALLENGES

From the academic research perspective, the scientific problems of active road noise control in automobiles are the information acquisition and sound field control within the acousto-vibratory coupled cavity under complex excitation. In terms of practical applications, the individual physiological differences of human subjects, changes in posture, and variable working conditions are all key issues that need to be addressed.

To further enhance the performance of active road noise control systems, future research, in addition to establishing more accurate models for analyzing the vibro-acoustic characteristics of the automotive cabin, can focus on the following directions: (1) the design of secondary sound sources with small volume,

strong low-frequency radiation performance, and adjustable spatial distribution of radiated sound, as well as the optimization of their placement within the automotive cabin; (2) the development of cost functions based on subjective perception; (3) non-contact methods for error signal acquisition; (4) rapid optimization methods for the number and location of reference signals and novel sensor devices; and (5) hardware algorithm solutions that balance performance and complexity.

IV. CONCLUSIONS

This paper provides an overview of the current application status of active control of road noise technology in the industry and its research progress over the past three decades. Recent research efforts at Nanjing University are introduced, focusing on three aspects: expanding the noise reduction bandwidth for global control systems, enhancing the noise reduction level for local control systems, and developing low-complexity adaptive algorithms for multi-reference feedforward systems. The challenges of active control of road noise and future research directions for performance improvement are discussed. It is believed that the noise reduction of RNC systems in production vehicles can be increased to 5 ~ 8 dB, given that 10 dB attenuation has been experimentally demonstrated under specific operating conditions.

V. ACKNOWLEDGMENT

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