In-car Noise Field Analysis and Multi-zone Noise Cancellation Quality Estimation

Hanchi Chen, Prasanga Samarasinghe and Thushara D. Abhayapala
Research School of Engineering
College of Engineering and Computer Science
Australian National University
Canberra, Australia

***Abstract*—The loudspeaker array plays a key role in an active noise cancellation (ANC) system. In most in car ANC systems, the car's pre-installed multimedia loudspeakers are employed as the secondary sources of the ANC system. In this paper, we evaluate the in-car loudspeaker system's capability in multi-zone noise field cancellation by analyzing the simultaneous noise field at multiple control regions inside a car cabin. We show that the average noise power in multi-zone spatial configurations can be expressed using a series of coefficients, and that the noise field can be decomposed into several basis noise patterns. Based on this model, we also estimate the integrated loudspeaker system's maximum noise cancellation capability, which can be used to assist design optimization. Through analyzing the noise field measurements in a car, we show that the car's integrated stereo loudspeaker system can attenuate the in-car noise by approximately 20 dB for the head position of two seats simultaneously, and up to 200 Hz.**

***Index Terms*—Active noise cancellation, spherical harmonics, loudspeaker array, sound field analysis**

I. Introduction

Minimization of interior cabin noise has been a key topic of research in the automobile industry for the last 15-20 years. This problem was first approached via passive noise cancellation methods, where physical treatments such as structural damping and acoustic absorption were used. However, with vehicle manufactures striving for more economical and light weight designs, the resulting car interiors invariably became more noisy due to the increased structural vibrations. These noise fields are dominant at low frequencies (e.g. 0-500 Hz) [1], hence the conventional passive noise cancellation approaches are less effective. In an attempt to solve this, active noise cancellation (ANC) methods were developed where secondary loudspeakers were proposed to attenuate measured noise inside the cabin [1]–[5]. With modern in-car entertainment systems providing 4-6 built-in loudspeakers, the addition of an active noise cancellation systems is considered to involve no greater cost [6].

In practice, in-car ANC is achieved by producing a signal out of phase with that generated by the noise source. The residual difference between these two signals is measured using a microphone placed inside the cabin, and is minimized using a feed-forward/feedback control system [7]. Feed-forward systems use an additional "reference signal" correlated with the noise signal to attenuate them individually, whereas Feedback systems use a single-input single-output system to attenuate overall measured noise [1]. Even though both methods are proven to deliver positive results, significant soundfield control over a single measurement point is highly constrained in space and is only capable of narrowband attenuation at about 40 Hz [8]. Addressing this issue, multi-input multi-output (MIMO) controllers with multiple microphones as error sensors (typically mounted on headrests) were introduced to increase spatial coverage [6], [8]–[11]. In recent work by Cheer *et al.* [8], MIMO controllers were shown to achieve attenuation levels up to 8 dB below 40 Hz and around 3 dB within 80-200 Hz for the specific case of road noise cancellation. In another study on MIMO noise control (not specific to car noise), Barkefors *et al.* [12] achieved noise reduction above 10 dB over a distributed set of 16 spatial samples in a 0.3×0.3 m region up to 500 Hz.

The existing MIMO controllers are restricted to a set of observation points arbitrarily distributed inside the car cabin. As a result, spatial control over continuous regions is strictly limited. In recent work [13], the authors focused on modeling vehicle-interior noise over a continuous spatial region such that noise attenuation can be achieved over the size similar to a human head up to $f = 500$ Hz. The region of interest was fixed at the front-left head rest and the authors derived the maximum spatial noise attenuation levels for a given loudspeaker configuration.

In this paper, we wish to significantly develop the above approach by considering multiple spatial regions (multi-zones [14]), preferably fixed at four head rest positions (driver, front-left, rear-left and rear-right) for increased user satisfaction. Based on noise recordings obtained at different driving conditions, we model the multi-zone noise field in terms of a set of basis noise patterns. We then use this model to predict the optimal noise cancellation capability of the in-built loudspeaker system. We derive results for simultaneous noise control over two or more control regions and analyze the maximum noise attenuation levels. The optimal performance evaluation presented in this paper is expected to largely facilitate the industrial designers when investigating the potential noise cancellation capability for a given interior and speaker system.

The paper is organized as follows. Section II defines the problem and Section III presents preliminaries. In Section IV, the theoretical aspects of multi-zone noise control and loudspeaker system performance are presented. Finally, Section V discusses experimental results based on real measurements.

II. Problem Formulation

Denote the unwanted noise pressure at point $\boldsymbol{x}$ as $P_n(\boldsymbol{x})$, and the sound pressure due to the loudspeakers as $P_c(\boldsymbol{x})$, the average residual noise energy within the control region S can be expressed as

$$E = \int_S |P_r(\boldsymbol{x})|^2 dS = \int_S |P_n(\boldsymbol{x}) + P_c(\boldsymbol{x})|^2 dS. \tag{1}$$

For simultaneous noise control over multiple regions, assuming that the size of each region is identical, then the overall average residual noise energy can be expressed as

$$E_{\text{avg}} = \frac{\sum_{j=1}^{J} E_j}{J} \tag{2}$$

where J is the total number of control regions.

In this work, rather than discussing the implementation of a complete in-car ANC system, we aim to analysis the relationship of noise fields between multiple noise control regions inside a car cabin, and estimate the optimal performance of simultaneous noise cancelling over two or more control regions by finding the minimum values of E_{avg} under various driving conditions, assuming that the car's pre-installed loudspeakers are used as secondary sources.

Since a complete in-car active noise cancellation system consists of multiple components, and each component may affect the final performance of the system, the estimated optimal noise cancellation performance may not be achievable in a real ANC system. However, the framework set out in this work can be used as a guidance for the design and assessment of in-car ANC systems, and to identify performance bottlenecks in an ANC system.

III. Preliminaries

Since we aim to investigate the average sound energy over a control region instead of single points, it is convenient to use the spherical harmonics decomposition to express the sound pressure within the region [15].

We assume that the region of interest S with radius R is a free space with no sound sources inside. The sound waves propagating inside the region are only due to sources outside the region. If we define a spherical coordinate with its origin located at the center of S, the sound pressure $P(r, \vartheta, \varphi, k)$ at a certain point and frequency within the region can be represented as a weighted sum of spherical harmonics [16]–[18],

$$P(r, \vartheta, \varphi, k) = \sum_{n=0}^{\infty} \sum_{m=-n}^{n} \alpha_{nm}(k) j_n(kr) Y_{nm}(\vartheta, \varphi), \tag{3}$$

where $k = 2\pi f/c$ is the wave number, f and c are the frequency and the wave propagation speed, respectively. α_{nm} are the spherical harmonic coefficients, $j_n(kr)$ is the spherical Bessel function of order n, and $Y_{nm}(\vartheta, \varphi)$ denotes the spherical harmonic of order n and degree m. $Y_{nm}(\vartheta, \varphi)$ are orthonormal over the sphere

$$\int_0^{\pi} \int_0^{2\pi} Y_{nm} Y^*_{n'm'} \sin\theta \, d\theta d\phi = \delta_{n-n', m-m'}. \tag{4}$$

We can then use the decomposition (3) to express the average sound energy within S. Due to the orthonormal property (4), we have

$$\int_S |P(\boldsymbol{x})|^2 dS = \int_0^R \int_0^{\pi} \int_0^{2\pi} P(\boldsymbol{x}) P(\boldsymbol{x})^* r^2 dr \sin\theta \, d\theta d\phi \tag{5}$$

$$= \sum_{n,m} \alpha_{nm} \alpha^*_{nm} \int_0^R j_n^2(kr) r^2 dr, \tag{6}$$

where $\boldsymbol{x} = (r, \theta, \phi)$, and the wave number k is omitted for simplicity. Define a new symbol W_n, such that

$$W_n = \Big(\int_0^R j_n(kr)^2 r^2 dr \Big)^{1/2}. \tag{7}$$

Since W_n is real, (6) becomes

$$\int_S |P(\boldsymbol{x})|^2 dS = \sum_{n,m} |\alpha_{nm} W_n|^2, \tag{8}$$

which shows that the average sound power level within S is equal to the sum of squared spherical harmonic coefficients with weighting W_n.

In the case of active noise cancellation, the residual noise field $P_r(\boldsymbol{x})$ in (1) thus have the average energy

$$\int_S |P_{\text{r}}(\boldsymbol{x})|^2 dS = \int_S |P_{\text{n}}(\boldsymbol{x}) + P_{\text{c}}(\boldsymbol{x})|^2 dS \tag{9}$$

$$= \sum_{n,m} |(\alpha^{(\text{n})}_{nm} + \alpha^{(\text{c})}_{nm}) W_n|^2, \tag{10}$$

where $\alpha^{(\text{n})}_{nm}$ and $\alpha^{(\text{c})}_{nm}$ are the spherical harmonic coefficients representing the noise field and the loudspeaker sound field, respectively.

IV. Multizone noise field analysis and ANC attenuation estimation

A. Characterization of multizone noise field

The noise field within a region can generally be seen as a weighted combination of multiple basis noise modes. In the case of in-car noise, the number of basis noise modes may vary under different driving conditions. Since the noise at different locations of the vehicle cabin is likely to be correlated, it is then desirable to consider the combined noise modes over multiple control regions, i.e.,

$$P_{\text{n}}(\boldsymbol{x}) = \sum_i g_i P_i(\boldsymbol{x}), \tag{11}$$

where $\boldsymbol{x} \in S_1, S_2 ...$, $P_i(\boldsymbol{x})$ denotes the ith global basis noise pattern at $\boldsymbol{x}$, and g_i are the weighting factors for each noise pattern. In theory, an infinite number of modes are needed to completely describe an arbitrary noise field within the regions of interest, however for a relatively small region and low frequencies, only a small number of noise modes are required for a good approximation of the noise field [19]. If the number of noise modes is small for a car cabin, then only a small number of sensors would be needed to monitor the noise field, and the number of independent secondary sources may also be reduced.

We define the control regions to be spherical regions of radius R, located somewhere inside the car cabin. Then, considering one of the control regions S_j, we can use the spherical harmonics decomposition (3) to decompose the noise field $P_{\rm n}(\boldsymbol{x}), x \in S_j$ as well as the basis patterns $P_i(\boldsymbol{x}), x \in S_j$, we can then express the noise field coefficients belonging to the jth control region α^j_{nm} using the corresponding coefficient $\alpha^{j,i}_{nm}$ of every basis pattern,

$$\alpha^j_{nm} = \sum_i g_i \alpha^{j,i}_{nm}. \tag{12}$$

We have shown that the average energy of a noise field is related to the spherical harmonic coefficients that represent the noise field by W_n. For convenience, we define the weighted spherical harmonic coefficients $c_{nm} = \alpha_{nm} W_n$, substituting into (12), we have

$$c^j_{nm} = \sum_i g_i c^{j,i}_{nm}. \tag{13}$$

Since we are considering the overall noise field over all of the control regions, it is convenient to write the coefficients of all regions in vector form, such that $\boldsymbol{c} = [c^1_{00}, c^1_{11} ... c^2_{00} ... c^j_{NN}]^T$, and $\boldsymbol{c}_i = [c^{1,i}_{00}, c^{1,i}_{11} ... c^{2,i}_{11} ... c^{j,i}_{NN}]^T$. Then from (13) and combining the coefficient of all control regions we have the vector representation

$$\boldsymbol{c} = \sum_i g_i \boldsymbol{c}_i. \tag{14}$$

In a constantly changing noise field, the weights g_i can be seen as random variables, hence the coefficient vector $\boldsymbol{c}$ becomes a random vector. In order to find a set of orthogonal basis vectors, we can calculate the covariance matrix $\boldsymbol{c}\boldsymbol{c}^H$, and by performing eigenvalue decomposition to the covariance matrix, we acquire a set of non-zero eigenvalues $\{\lambda_i\}$ and their corresponding eigenvectors $\boldsymbol{c}_i$. $\{\lambda_i\}$ becomes an estimation of the random variables $\{g_i\}$, i.e., $E\{\|g_i\|\} = \lambda_i$. Furthermore, the sum of all eigenvalues is equal to the average energy of the noise field. The covariance matrix $\boldsymbol{c}\boldsymbol{c}^H$ can be estimated by taking multiple snapshots of the real noise field, similar to the MUSIC DOA estimation algorithm [20].

The number of significant eigenvalues would indicate the dimensionality or sparsity of the multi-zone noise field, which determines the minimum number of independent secondary sources required to effectively cancel the noise field. If less than the minimum number of loudspeakers are used, the system becomes undetermined and the ANC performance is expected to degrade significantly, this is confirmed by our experiment results.

By converting the eigenvectors $\{\boldsymbol{c}_i\}$ back to α_{nm} through $\alpha_{nm} = c_{nm}/W_n$, we acquire the unweighted spherical harmonic basis, which can be reconstructed into noise patterns via (3). These noise patterns together form a complete basis for the global noise field over the control regions. Various signal processing techniques such as Direction-of-Arrival estimation can be applied to these basis noise modes to identify noise impinging directions and determine optimal secondary loudspeaker placement.

B. Estimation of ANC performance with limited driving signal power

In order to analysis the noise cancelling performance, we need to model the responses of the secondary loudspeakers. We use the spherical harmonic method to model the loudspeaker response over a region, and denote the spherical harmonic coefficients due to the loudspeakers as H (instead of α), and form the loudspeaker channel matrix as

$$\boldsymbol{H} = \begin{bmatrix} H^{1,1}_{0\,0} & H^{1,2}_{0\,0} & H^{1,3}_{0\,0} & \cdots \\ H^{1,1}_{11} & H^{1,2}_{1-1} & H^{1,3}_{1-1} & \cdots \\ \vdots & \vdots & \vdots & \cdots \\ H^{2,1}_{0\,0} & H^{2,2}_{0\,0} & H^{2,3}_{0\,0} & \cdots \\ \vdots & \vdots & \vdots & \ddots \end{bmatrix} \tag{15}$$

where $H^{j,i}_{nm}$ being the spherical harmonic coefficient of order n and degree m, associated with the jth control region, due to the ith loudspeaker playing a unit signal. We emphasis that the channel matrix (15) is not to be confused with the commonly used point-to-point channel matrix, since (15) represents the response of the loudspeakers over multiple spatial regions. Although, a point-to-point channel matrix can be derived from (15) for any point within the control regions using (3) as in [21].

A commonly used method for sound field reproduction or noise cancellation is the pressure matching method, which involves inverting the channel matrix $\boldsymbol{H}$. In order to minimize the average sound energy over all control regions (9), we define the weighted loudspeaker channel matrix $\boldsymbol{T}$, whose size is identical to that of $\boldsymbol{H}$, with its elements given by

$$T^{j,i}_{nm} = H^{j,i}_{nm} W_n. \tag{16}$$

The solution for loudspeaker driving signals that minimizes (9) can be written as

$$\boldsymbol{D} = -(\boldsymbol{T}^H \boldsymbol{T})^{-1} \boldsymbol{T}^H \boldsymbol{c} \tag{17}$$

and the residual error vector is

$$\boldsymbol{e} = \boldsymbol{c} + \boldsymbol{T}\boldsymbol{D} = (\boldsymbol{I} - \boldsymbol{T}(\boldsymbol{T}^H \boldsymbol{T})^{-1} \boldsymbol{T}^H)\boldsymbol{c}. \tag{18}$$

The average residual energy is equal to $\|\boldsymbol{e}\|^2$.

A limitation of this method is that the amplitude of the loudspeaker driving signal is unbounded. Although a regularization can be added to the matrix inversion in (17) to avoid extremely high driving signals, there is no strict upperbound to the loudspeaker output power. From a practical point of view, driving a loudspeaker beyond its linear operating range would result in harmonic distortions, which introduces additional noise in the control regions. In order to avoid this problem, we define the optimization problem

$$\min f(\boldsymbol{D}) = \|\boldsymbol{c}+\boldsymbol{TD}\|, \text{subject to } |D_i| \leqslant L, i = 1, 2... \quad (19)$$

where D_i are the elements of $\boldsymbol{D}$ and represent the driving signal for the ith loudspeaker, $\|\cdot\|$ denotes 2-norm, L is a constant which sets the volume upper bound for each loudspeaker. The noise energy attenuation can be represented as

$$A = \frac{\int_{S_1,S_2..} |P_r(\mathbf{x})|^2 d\mathbf{x}}{\int_{S_1,S_2..} |P_r(\mathbf{x})|^2 d\mathbf{x}} = \frac{\|\boldsymbol{c}+\boldsymbol{TD}\|^2}{\|\boldsymbol{c}\|^2} \quad (20)$$

where $\boldsymbol{D}$ is the solution to (19).

V. Experimental results analysis

A. Experiment Setup

In our experiment, we aim to investigate the noise field complexity within a 2005 Ford Falcon XR6 sedan, under various driving conditions; as well as examine the noise cancelling potential of the multimedia loudspeakers installed in the car. The regions of interest are chosen to be spherical regions located at the head position of each of the four seats, the radius of each region is set to 10 cm, which covers the size of a human head.

For this experiment, we focus on the noise below 200 Hz. Using (8), we can calculate the relative contribution of each spherical harmonic mode towards the total noise energy within the control regions, at $f = 200$ Hz we have

$$\frac{\int_S |P_{00}(\boldsymbol{x})|^2 dS}{\int_S |P(\boldsymbol{x})|^2 dS} = \frac{|\alpha_{00} W_n|^2}{\sum_{n,m} |\alpha_{nm} W_n|^2} \approx 0.972 \quad (21)$$

thus the 0th order spherical harmonic accounts for the vast majority of the noise energy within the control regions, for frequencies below 200Hz, the contribution of the 0th mode is even higher (99.3% at 100 Hz). Therefore, in our experiments, we only monitor the 0th order spherical harmonic for each control region, which can be done by placing a single omni-direction microphone at the center of each region. We note that we measure only the 0th mode spherical harmonic because at low frequencies, the 0th mode contributes to the majority of the noise energy, not because we believe the noise field is isotropic. For noise field analysis of large region and higher frequencies, higher-order microphones are required, such as the Eigenmike.

The recording system we use consists of four AKG CK92 omnidirectional condenser microphones, connected to a Tube-Fire 8 audio interface via four AKG SE300B microphone pre-amps. The synchronous audio streams are recorded using a Macbook, which is connected to the TubeFire 8 via firewire.

We record the noise field at the four control regions simultaneously for various driving conditions, including the pure engine noise recording, where the car is parked in a relatively quiet place and the engine ran at 2000 rpm. For each driving condition, we record the noise for 10 seconds. The recording is then split into 100 frames and transformed into spherical harmonic coefficients $\alpha_{00}^j(k)$ at different frequency bins for further analysis.

TABLE I
Noise field eigenvalues for freeway driving condition and pure engine noise

100 km/h	40 Hz	80 Hz	120 Hz	160 Hz	200 Hz
λ_1	1.000	1.000	1.000	1.000	1.000
λ_2	0.292	0.282	0.498	0.476	0.292
λ_3	0.062	0.207	0.181	0.372	0.102
λ_4	0.007	0.139	0.049	0.092	0.053
Engine Only	40 Hz	80 Hz	120 Hz	160 Hz	200 Hz
λ_1	1.000	1.000	1.000	1.000	1.000
λ_2	0.033	0.315	0.108	0.293	0.042
λ_3	0.005	0.095	0.018	0.106	0.031
λ_4	0.000	0.018	0.003	0.045	0.015

The Ford sedan has four full-band loudspeakers installed, two of which are integrated at the bottom of either of the front doors, while the other two are placed behind each rear seat. However, the car's audio playback system only supports stereo signals, which means the two loudspeakers on the left side simultaneously play the left channel of the stereo signal, and the same goes for the right channel.

We obtain the loudspeaker channel matrix by measuring the impulse response at the region of interest due to the left channel and right channel separately, and then calculating the corresponding sound field coefficients for each frequency bin, in the same way as we obtain the noise field measurements. The channel matrix takes the form of (15) The 0th order sound fields at 4 regions and the stereo speaker system result in a 4-by-2 channel matrix for each frequency bin.

In order to estimate the noise cancellation capability of the in-car loudspeakers in each driving condition, we solve (19) for each of the 100 snapshots in every recording, and calculate the expected residual noise energy for each snapshot. The value of L is chosen such that the sound energy at the regions of interest due to each loudspeaker is no more 3 times more than that due to the noise. We then calculate the average noise energy attenuation using

$$A = \frac{\sum_{l=1}^{100} \|\boldsymbol{c}_l + \boldsymbol{TD}_l\|^2}{\sum_{l=1}^{100} \|\boldsymbol{c}_l\|^2}, \quad (22)$$

where $\boldsymbol{c}_l$ and $\boldsymbol{D}_l$ are the weighted coefficient vectors and the optimal driving signals for the snapshots in each recording, respectively.

B. Data Analysis

We first investigate the dimensionality of the combined noise field over the four control regions by observing the eigenvalues of the estimated covariance matrix of the spherical harmonic coefficients. We normalize the eigenvalues and sort them from the largest to the smallest, the results for pure engine noise and the noise when driving at 100 km/h are shown in Table I. We can see from Table I that the eigenvalues of the engine noise are almost always smaller than the corresponding eigenvalues of the freeway driving condition (100 km/h). In

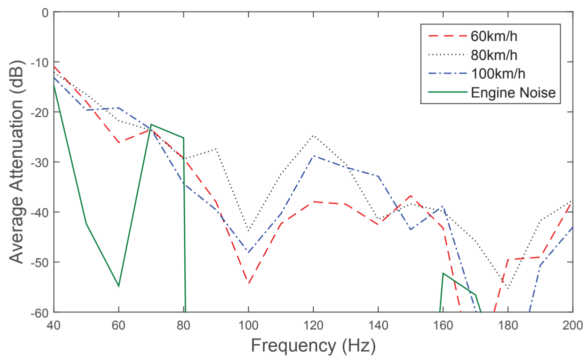

Fig. 1. Expected noise power attenuation after noise cancellation in the two front seats only.

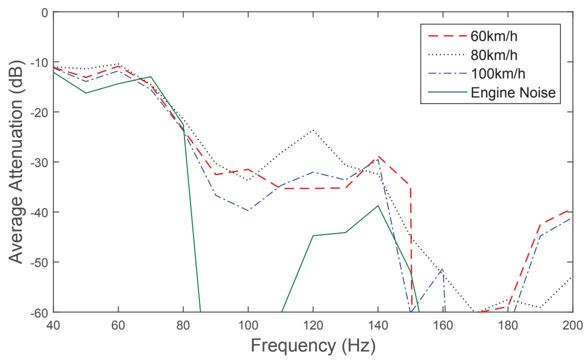

Fig. 2. Expected noise power attenuation after noise cancellation in the two right side seats only.

the case of engine noise, the fourth eigenvalue is in the order of 0.01 for most frequencies, therefore the noise field may be modelled using 3 noise modes in (12), without significant loss of accuracy. As a result, in order to effectively cancel the engine noise over the four control regions simultaneously, a minimum of 3 loudspeakers would be sufficient, assuming that the loudspeaker channels have sufficient diversity.

On the other hand, the noise field of the freeway driving condition is more complicated, the fourth eigenvalues are above 0.01 for all frequencies above 40 Hz. Therefore at least four independent loudspeakers are required to effectively cancel the noise within the control regions simultaneously.

Since the car's loudspeakers can only play stereo signals, and that the combined noise fields require no less than 4 independent loudspeaker channels to effectively control, we do not expect a high noise energy attenuation over 3 or 4 seats. However, we expect the loudspeakers to simultaneously cancel the noise over two control regions with good results. In order to validate our expectations, we use (22) to calculate the expected noise attenuation for simultaneous noise cancellation for 2, 3 and 4 seats, the results are shown in FIGs. 1-4. The noise cancellation performance for the two front seats only is shown in FIG. 1. The attenuations are calculated for frequencies from 40 Hz to 200 Hz, and for driving speeds at 60 km/h, 80 km/h and 100 km/h. The attenuation for the engine noise is also included in the figure. We can see from FIG. 1 that the attenuation for all three driving speeds are very similar. The residual noise level is highest at 40 Hz, and gradually reduces to around -40 dB for all three driving speeds. The engine noise, on the other hand, can be effectively cancelled at most frequency bins. We believe this is because of the low dimensionality of the engine noise field, as is shown in Table I.

Since we are only considering the 0th order coefficients in our calculations, while ignoring the other coefficients which contribute to approximately 1 percent of total noise energy, the upper bound of actual achievable attenuation would be around 20 dB, depending on the loudspeakers' ability to attenuate the higher order coefficients.

FIG. 2 shows the results for simultaneous noise control for the two right side seats. A trend similar to that in FIG. 1 can be observed. We believe that the reason for the increasing attenuation over frequency is due to the impact of wavelength on loudspeaker channels, where at low frequency, the sound pressure at two different seats due to one particular loudspeaker is very similar. Therefore the loudspeaker channel matrix is highly coupled at low frequencies, resulting in less noise attenuation under the same output power constraint. FIG. 3 illustrates the expected ANC performance for simultaneous 3-seat noise control (two front seats and left passenger seat). As expected, the noise energy reduction is significantly worse than the two-seat cases, with around 10 dB reduction across all frequency bins of interest. We also notice that the engine noise is no longer easier to cancel than the other noise fields apart from a few frequency bands (40-60 Hz). This is consistent with Table I, where the third and fourth eigenvalues of engine noise at 40 Hz are very small, indicating a sparse noise field with 2 degrees of freedom, therefore the noise field can be controlled by a stereo system. We also include FIG. 4 which depicts the four-seat ANC performance. Compared to FIG. 3, the attenuation is even smaller at around 6-7 dB. However, the ANC performance is once again consistent over different driving speeds. From this observation, we estimate that the noise field at different driving speeds are similar, and that a loudspeaker array's capability of controlling in-car noise does not vary greatly at different driving speeds.

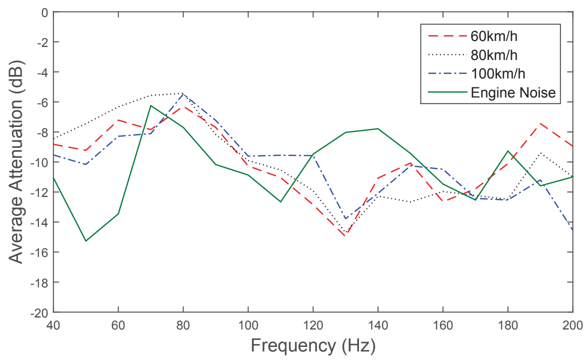

Fig. 3. Expected noise power attenuation after noise cancellation in the two front seats and the left passenger seat.

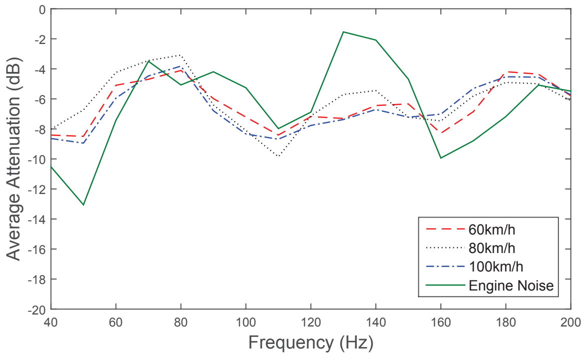

Fig. 4. Expected noise power attenuation after noise cancellation in all four seats.

The attenuation of the engine noise is often lower that of the noise fields under various driving conditions. However, from our subjective tests, the majority of the noise in the car cabin came from the tires and suspension, the engine noise only plays a small part in the overall perceived noise. Therefore, it is understandable that the overall noise reduction is different from the engine noise suppression under the same conditions.

In general, we can conclude that the integrated loudspeakers, when used as a stereo system, are capable of simultaneously cancelling the in-car noise fields at the head position of two seats, for frequencies up to 200 Hz. In order to control the noise over more regions, additional independent loudspeakers are required. We expect the multi-zone ANC performance of the four integrated loudspeakers to improve significantly, if they could be driven separately.

VI. Conclusion

In this work, we show that the average noise energy within a region can be represented by the spherical harmonic coefficient associated with the noise field. Using this representation, we present a method of characterizing the noise pattern and average noise energy over multiple regions. Based on this, we develop a framework to estimate the in-car loudspeaker's capability of simultaneously controlling the in-car noise field at multiple regions.

Through analyzing the multi-zone in-car noise data acquired from field tests, we show that a stereo speaker system can effectively control the low frequency in-car noise over two regions, and at least four independent loudspeakers are needed for effective noise control over four regions.

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