Reference Signal Generation for Broadband ANC Systems in Reverberant Rooms

Fei Ma, Wen Zhang, Thushara D. Abhayapala
Contact: {fei.ma, wen.zhang, thushara.abhayapala}@anu.edu.au

Contribution

- Develop a time-domain sound field separation method over a sphere.
- Propose to use the outgoing field on a sphere surrounding the primary source as the reference signal for broadband active noise control (ANC) systems in reverberant rooms.

The reference signal problem

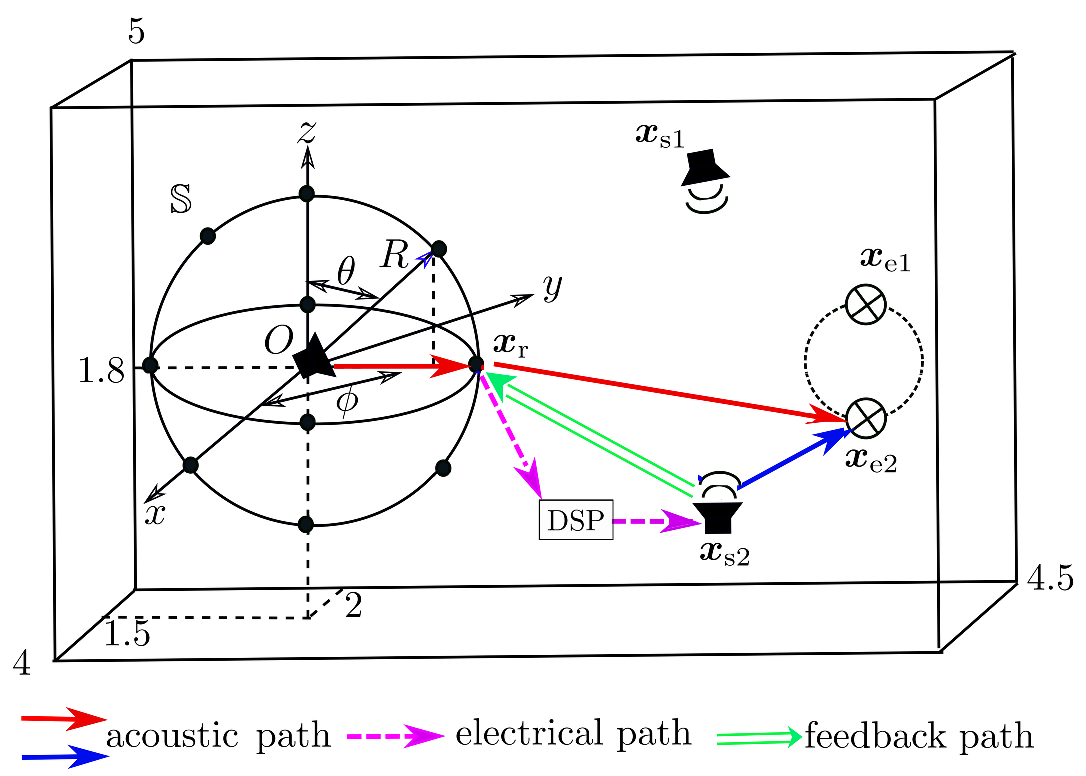


Figure 1: A broadband ANC system in a reverberant room.

- In the reverberant room as shown in Fig. 1, there is a primary source, two secondary sources located at $\boldsymbol{x}_{\rm s1}$ and $\boldsymbol{x}_{\rm s2}$, respectively, and two error sensors $\otimes$ located at $\boldsymbol{x}_{\rm e1}$ and $\boldsymbol{x}_{\rm e2}$, respectively.
- The broadband ANC system pass a reference signal, which provides advanced information of the primary noise $P_{\rm p}(n, \boldsymbol{x}_{\rm e})$ at the error sensor, through a digital signal processing (DSP) board to generate the secondary noise [1].
- The measurement of the reference sensor at position $\boldsymbol{x}_{\rm r}$ at time n is

$$P_{\rm r}(n, \boldsymbol{x}_{\rm r}) = P_{\rm p}(n, \boldsymbol{x}_{\rm r}) + P_{\rm s}(n, \boldsymbol{x}_{\rm r}) + P_{\delta}(n, \boldsymbol{x}_{\rm r}), \quad (1)$$

  - $P_{\rm p}(n, \boldsymbol{x}_{\rm r})$ the primary source output,
  - $P_{\rm s}(n, \boldsymbol{x}_{\rm r})$ the secondary source feedback,
  - $P_{\delta}(n, \boldsymbol{x}_{\rm r})$ the room reverberation.
- The presence of $P_{\rm s}(n, \boldsymbol{x}_{\rm r})$ and $P_{\delta}(n, \boldsymbol{x}_{\rm r})$ reduces the coherence between the reference sensor measurement $P_{\rm r}(n, \boldsymbol{x}_{\rm r})$ and the primary noise $P_{\rm p}(n, \boldsymbol{x}_{\rm e})$ at the error sensor.
- The performance of the broadband ANC system deteriorates if the reference sensor measurement $P_{\rm r}(n, \boldsymbol{x}_{\rm r})$ is used as the reference signal directly [1].

A time-domain sound field separation method over a sphere

The sound field $P(n, R, \theta, \phi)$ on a sphere $\mathbb{S}$ of radius R can be decomposed as [2]

$$P(n, R, \theta, \phi) = \sum_{u=0}^{\infty} \sum_{v=-u}^{u} \alpha_{uv}(n, R) Y_u^v(\theta, \phi), \quad (2)$$

- (R, θ, ϕ) are spherical coordinates,
- $Y_u^v(\theta, \phi)$ is the spherical harmonics of order u and degree v

$$Y_u^v(\theta,\phi) \equiv \begin{cases} \sqrt{\frac{(2u+1)(u-|v|)!}{2\pi(u+|v|)!}}\mathcal{P}_u^{|v|}(\cos(\theta))\cos(|v|\phi), & v>0,\\ \sqrt{\frac{(2u+1)(u-|v|)!}{4\pi(u+|v|)!}}\mathcal{P}_u^{|v|}(\cos(\theta)), & v=0,\\ \sqrt{\frac{(2u+1)(u-|v|)!}{2\pi(u+|v|)!}}\mathcal{P}_u^{|v|}(\cos(\theta))\sin(|v|\phi), & v<0,\end{cases}$$

$\mathcal{P}_u^{|v|}(\cdot)$ is an associated Legendre function,

- the spherical harmonic coefficients $\alpha_{uv}(n, R)$ are given by [2]

$$\alpha_{uv}(n, R) = \int_{\theta=0}^{\pi}\int_{\phi=0}^{2\pi} P(n, R, \theta, \phi) Y_u^v(\theta, \phi)\sin(\theta) d\theta d\phi. \quad (3)$$

The outgoing field $P^{\rm O}(n, R, \theta, \phi)$ on a sphere of radius R is

$$P^{\rm O}(n, R, \theta, \phi) \approx \sum_{u=0}^{N_R} \sum_{v=-u}^{u} \zeta_{uv}^{\rm O}(n, R) Y_u^v(\theta, \phi), \quad (4)$$

- $\zeta_{uv}^{\rm O}(n, R)$ are the outgoing field coefficients

$$\zeta_{uv}^{\rm O}(n, R) \approx \sum_{q=1}^{Q} \gamma_q Y_u^v(\theta_q, \phi_q) \sum_{n'=0}^{T_n} \times \Big\{ h_1^u(n')\big[P(n-n', R, \theta_q, \phi_q) - P(n-1-n', R, \theta_q, \phi_q)\big] + \rho c h_2^u(n')\big[V(n-n', R, \theta_q, \phi_q) - V(n-1-n', R, \theta_q, \phi_q)\big]\Big\},$$

- N_R is the truncation order of the outgoing field [3],
- $P(n, R, \theta_q, \phi_q)$ and $V(n, R, \theta_q, \phi_q)$ are the pressure and radial particle velocity, respectively,
- $(\theta_1, \phi_q)_{q=1}^{Q}$ are sampling point positions,
- T_n is the number of samples corresponding to $2R/c$,
- c is the speed of sound, ρ is the density of air,
- $h_1^u(n)$ and $h_2^u(n)$ are impulse responses as shown in Fig. 2.

Simulation: Sound field separation on a sphere

- We have three point sources inside of the sphere $\mathbb{S}$ of radius $R = 0.34$ m, and another three point sources at outside of the sphere $\mathbb{S}$.

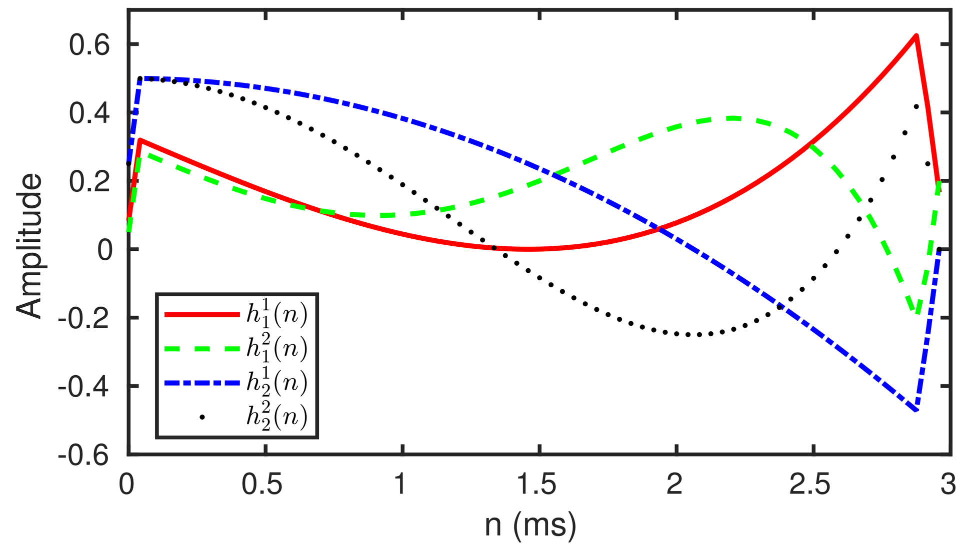
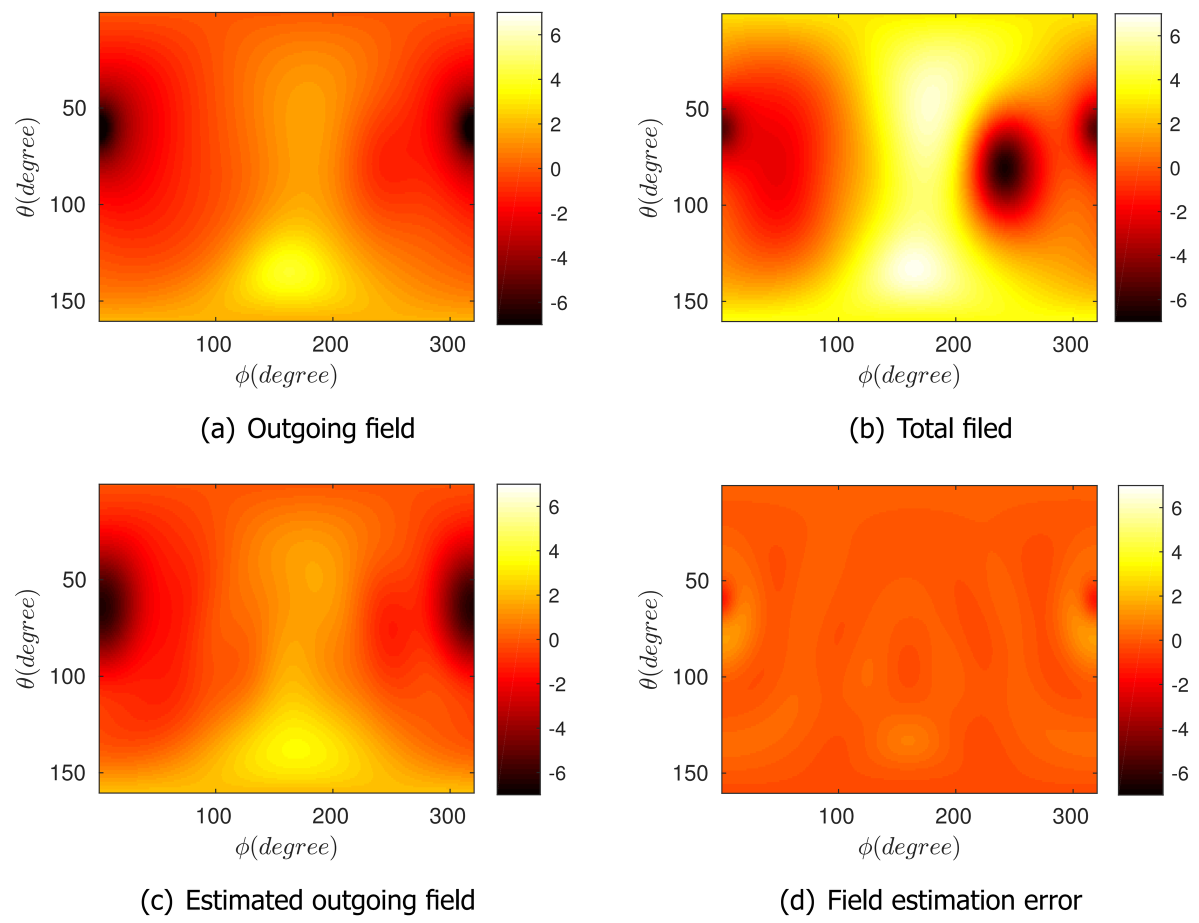


Figure 2: The impulse responses $h_v^u(n)$ for $v = 1, 2$, $u = 1, 2$, and $R/c = 1.5$ ms.

- The point sources generate sounds $\sum_{l=1}^{100} a_l \cos(2\pi(f_0 + \delta_f \times l)n)$, where $f_0 = 100$ Hz, $\delta_f = 5$ Hz.
- In Eq. (4), we truncate the spherical harmonics to order $N_R = 5$. The pressure and radial partial velocity on the sphere $\mathbb{S}$ are sampled at seventy-two points according to the 5-th Gauss sampling scheme.
- We conduct sound field separation over $T = 30$ ms. The field estimation error is small over the whole sphere $\mathbb{S}$.



(a) Outgoing field (b) Total filed (c) Estimated outgoing field (d) Field estimation error

Figure 3: Sound field separation simulation: At time instant n = 23.5 ms, the amplitudes of (a) the outgoing field, (b) the total field, (c) the estimated outgoing field, and (d) the field separation error on the sphere $\mathbb{S}$.

Simulation: Noise cancellation at two error sensors

- The simulation environment is shown in Fig. 1. We have a primary source at the origin O, two secondary sources at $(\pm 0.75, 0.75, 0.0)$ m, and two error sensors at $(\pm 0.09, 2.0, 0.0)$ m.
- The primary source generates a broadband noise same as in previous section.
- We propose an ANC system that uses the separated outgoing field as the reference signal, and compare its performance with the conventional ANC system [4].
- The outgoing field truncation order is $N_R = 3$. The pressure and radial partial velocity on the sphere $\mathbb{S}$ are sampled at thirty-two points according to the 3-th Gauss sampling scheme.
- We increase the reflection coefficients from $[0.71, 0.72, 0.74, 0.76, 0.78, 0.8]$ all to 0.9 at $n = 4$ s to simulate a time-varying environment.
- Denote the noise power reduction at the error sensor be

$$\xi(n) = 10\log_{10}\frac{P_e(n)^2}{P_p(n)^2}, \quad (5)$$

where $P_p(n)$ and $P_e(n)$ are the primary noise and residual noise at the error sensor, respectively.

- Figure 4 depicts the noise power reductions at error sensor one, i.e., $(0.09, 2, 0)$ m achieved by the proposed system $\xi_1(n)$, and by the conventional system $\xi_2(n)$.
- In Fig. 4, the performance of the proposed system is less affected by the environmental changes.

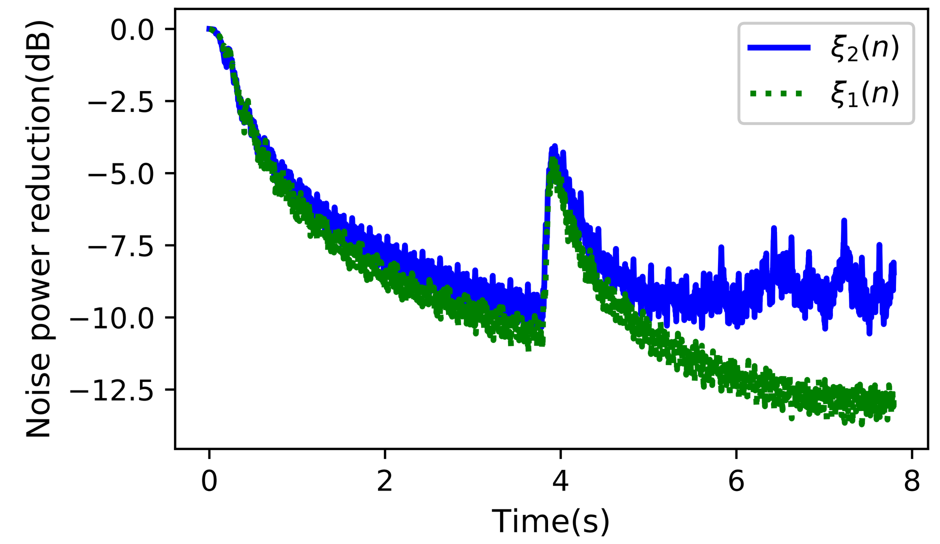


Figure 4: Noise cancellation simulation: The noise power reductions at error sensor one $(0.09, 2.0, 0.0)$ m achieved by the proposed system $\xi_1(n)$, and by the conventional system $\xi_2(n)$.

Future work

- Use the sound field separation method for monitoring a machine in a reverberant room in real-time.
- Use high order microphones to reduced the number of microphones needed for sound field separation.

References

[1] S. M. Kuo and D. R. Morgan, Active Noise Control Systems: Algorithms and DSP Implementations. John Wiley & Sons, Inc., 1995.

[2] E. G. Williams, Fourier acoustics: sound radiation and nearfield acoustical holography. Academic press, 1999.

[3] D. B. Ward and T. D. Abhayapala, "Reproduction of a plane-wave sound field using an array of loudspeakers," IEEE Transactions on speech and audio processing, vol. 9, no. 6, pp. 697–707, 2001.

[4] M. T. Akhtar, M. Abe, M. Kawamata, and M. Mitsuhashi, "A simplified method for online acoustic feedback path modeling in multichannel active noise control systems," in 2008 SICE Annual Conference, Aug 2008, pp. 50–54.

Australian National University

ANU College of Engineering & Computer Science