# TIME-DOMAIN ACOUSTIC CONTRAST CONTROL WITH SPATIAL UNIFORMITY CONSTRAINT FOR PERSONAL AUDIO SYSTEMS

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## Introduction

- Personal Audio Systems (PAS) aim to generate multiple sound zones in a shared space
- Acoustic Contrast Control (ACC) method is one of the most popular methods
- **Time-domain broadband ACC (BACC)** method suffers from pool sound quality due to
  1) uneven frequency response
  2) non-uniform sound field in the bright zone
- The first problem has been tackled by applying a Response Trend Estimation (RTE) constraint to BACC method [1][2]
- This paper presents the Spatial Uniformity Constraint (SUC) to overcome the second problem

## Problem formulation

- System setup (Fig. 1)
  - 10 speakers in an arc array
  - 8 microphones in each zone
- Input signal $x[n]$ assumed to be a Dirac delta function
- Control filter for the $l$-th speaker: $I$-tap FIR filter $\mathbf{w}_l$
- RIR from the $l$-th speaker to the $m$-th mic: $K$-tap FIR filter $\mathbf{h}_{ml}$
- The sound pressure at the $m$-th mic due to the $l$-th speaker is

$$p_{\mathrm{B},ml}[n]=\sum_{i=0}^{I-1}h_{\mathrm{B},ml}[n-i]w_l[i]$$

- Written in vector form as

$$\mathbf{p}_{\mathrm{B},ml}=\mathbf{H}_{\mathrm{B},ml}\mathbf{w}_l$$

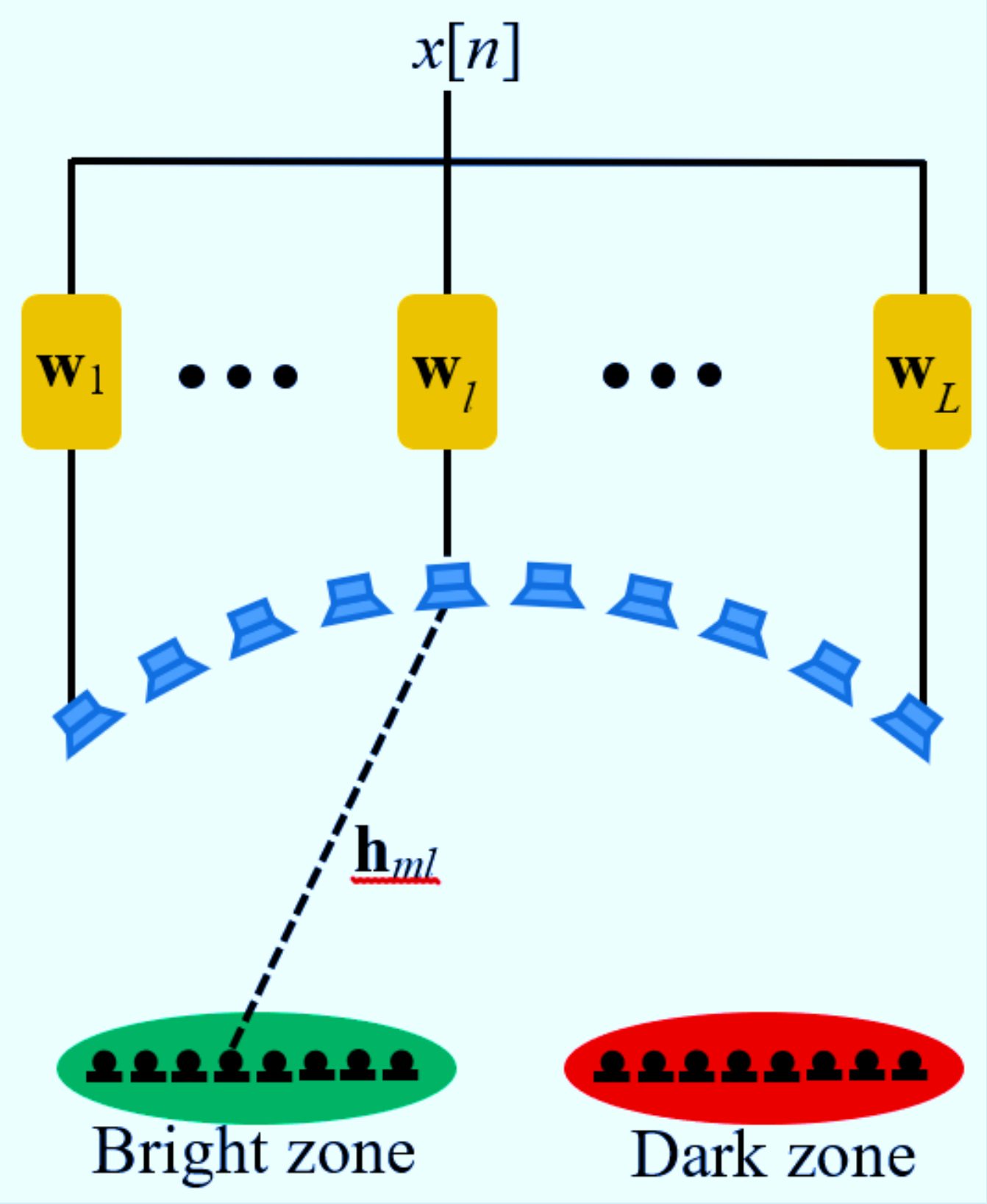

Fig. 1. Block diagram of PAS.

- The total sound pressure at the $m$-th mic due to all the speakers is

$$\mathbf{p}_{\mathrm{B},m}=\sum_{l=1}^{L}\mathbf{p}_{\mathrm{B},ml}=\sum_{l=1}^{L}\mathbf{H}_{\mathrm{B},ml}\mathbf{w}_l=\mathbf{H}_{\mathrm{B},m}\mathbf{w}$$

- The sound pressure at all the mics in the bright zone $\mathbf{p}_\mathrm{B}=\mathbf{H}_\mathrm{B}\mathbf{w}$
- The sound pressure at all the mics in the dark zone $\mathbf{p}_\mathrm{D}=\mathbf{H}_\mathrm{D}\mathbf{w}$
- **BACC** cost function [1]

$$J_{\mathrm{BACC}}=\frac{\mathbf{w}^\mathrm{T}\mathbf{R}_\mathrm{B}\mathbf{w}}{\mathbf{w}^\mathrm{T}\mathbf{R}_\mathrm{D}\mathbf{w}+\lambda\mathbf{w}^\mathrm{T}\mathbf{w}},\ \text{where } \mathbf{R}_\mathrm{B}=\mathbf{H}_\mathrm{B}{}^\mathrm{T}\mathbf{H}_\mathrm{B},\ \mathbf{R}_\mathrm{D}=\mathbf{H}_\mathrm{D}{}^\mathrm{T}\mathbf{H}_\mathrm{D}$$

- **BACC-RTE** cost function [2]

$$J_{\mathrm{RTE}}=\frac{\mathbf{w}^\mathrm{T}\mathbf{R}_\mathrm{B}\mathbf{w}}{(1-\alpha)\mathbf{w}^\mathrm{T}\mathbf{R}_\mathrm{D}\mathbf{w}+\alpha\mathbf{w}^\mathrm{T}\mathbf{C}_{\mathrm{RTE}}\mathbf{w}+\lambda\mathbf{w}^\mathrm{T}\mathbf{w}}$$

$\mathbf{C}_{\mathrm{RTE}}$ is the RTE constraint

## Proposed BACC-RTE-SUC method

- The sound pressure at the $m$-th microphone at frequency $f$ is

$$P_{\mathrm{B},m}(f)=\sum_{n=0}^{I+K-2}\mathbf{p}_{\mathrm{B},m}[n]\mathrm{e}^{-\mathrm{j}2\pi nfT_\mathrm{s}}=\mathbf{w}^\mathrm{T}\mathbf{H}_{\mathrm{B},m}{}^\mathrm{T}\underline{\boldsymbol{s}}(f)$$

- The **Spatial Uniformity Constraint (SUC)** is defined as mean square of the sound pressure differences between microphones, i.e.,

$$SUC=\frac{1}{C}\sum_{j=1}^{J}\sum_{m=1}^{M_\mathrm{B}-2b+1}\left|P_{\mathrm{B},m+b}(f_j)-P_{\mathrm{B},m}(f_j)+P_{\mathrm{B},m+2b-1}(f_j)-P_{\mathrm{B},m+b-1}(f_j)\right|^2$$

$$SUC=\frac{1}{C}\mathbf{w}^\mathrm{T}\mathcal{R}\left\{\sum_{j=1}^{J}\mathbf{H}_\mathrm{B}{}^\mathrm{T}\underline{\boldsymbol{u}}(f_j)\mathbf{V}_\mathrm{b}\mathbf{V}_\mathrm{b}{}^T\underline{\boldsymbol{u}}(f_j)^\mathrm{H}\mathbf{H}_\mathrm{B}\right\}\mathbf{w}$$

$$=\mathbf{w}^\mathrm{T}\left\{\frac{1}{C}\mathbf{H}_\mathrm{B}{}^\mathrm{T}\mathcal{R}\left\{\sum_{j=1}^{J}\underline{\boldsymbol{u}}(f_j)\mathbf{V}_\mathrm{b}\mathbf{V}_\mathrm{b}{}^T\underline{\boldsymbol{u}}(f_j)^\mathrm{H}\right\}\mathbf{H}_\mathrm{B}\right\}\mathbf{w}$$

$$=\mathbf{w}^\mathrm{T}\left\{\frac{1}{C}\mathbf{H}_\mathrm{B}{}^\mathrm{T}\mathcal{R}\left\{\underline{\boldsymbol{U}}\mathbf{V}\underline{\boldsymbol{U}}^H\right\}\mathbf{H}_\mathrm{B}\right\}\mathbf{w}$$

$$=\boxed{\mathbf{w}^\mathrm{T}\mathbf{C}_{\mathrm{SUC}}\mathbf{w}}$$

- **BACC-RTE-SUC cost function** is defined as ($\alpha+\beta+\gamma=1$)

$$J_{\mathrm{SUC}}=\frac{\mathbf{w}^\mathrm{T}\mathbf{R}_\mathrm{B}\mathbf{w}}{\mathbf{w}^\mathrm{T}\left[\gamma\mathbf{R}_\mathrm{D}+\alpha\mathbf{C}_{\mathrm{RTE}}+\beta\mathbf{C}_{\mathrm{SUC}}\right]\mathbf{w}+\lambda\mathbf{w}^\mathrm{T}\mathbf{w}}$$

- The optimal solution to minimise $J_{\mathrm{SUC}}$ is proportional to the eigenvector corresponding to the largest eigen value of the matrix $(\gamma\mathbf{R}_\mathrm{D}+\alpha\mathbf{C}_{\mathrm{RTE}}+\beta\mathbf{C}_{\mathrm{SUC}}+\lambda\mathbf{I})^{-1}\mathbf{R}_\mathrm{B}$

## Experiments

- Room Impulse Responses (RIRs) were measure in an hemi-anechoic chamber, as illustrated in Fig. 2.
- 60 speakers uniformly placed along a circular truss with a radius of 1.5 m
- 10 speakers in the red rectangle in Fig. 2 used in this paper
- 2 zones separated by 0.8 m
- 8 microphones in each zone

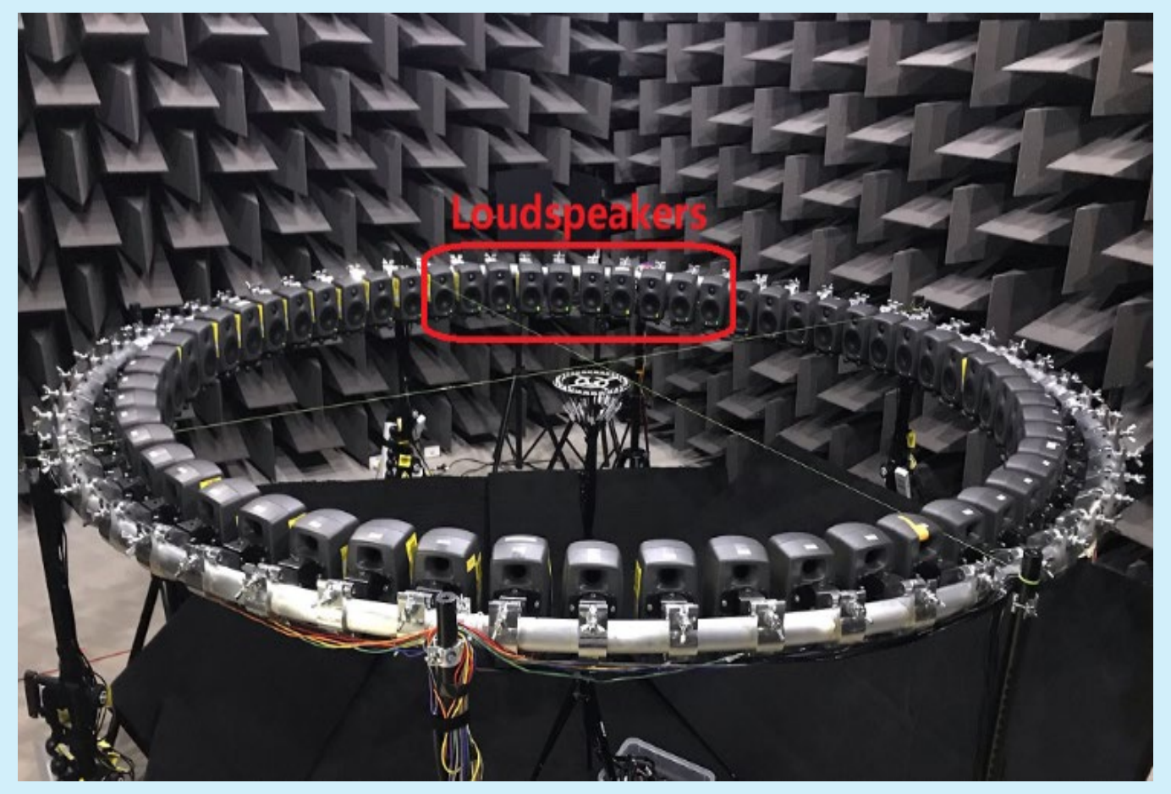

Fig. 2. Experimental setup

- Log sweep sine signals used to excite the speakers
- Original sampling rate 48 kHz down sampled to 8 kHz for simulations
- Control filter length I = 128
- RIRs filter length K = 256
- Regularization parameter $\lambda$ is $10^{-10}$ times the largest eigenvalue of the matrix $\mathbf{R}_\mathrm{D}$
- The weighting parameters $\alpha=0.6$, $\beta=0.3$, $\gamma=0.1$

## Results

- Fig. 3(a) shows that the sound pressure magnitudes are different at different positions for the BACC-RTE method.
- Fig. 3(b) demonstrates the proposed BACC-RTE-SUC method to have a uniform sound pressure distribution in the bright zone without affecting the frequency responses.
- Fig. 4 depicts that the sound pressure magnitudes in the bright zone deviate by up to 8.5 dB at 500 Hz and 1000 Hz for BACC-RTE method; by contrast, the BACC-RTE-SUC method shows a uniform sound pressure level within 1.5 dB.
- The maximum sound magnitude difference in the bright zone and the acoustic contrast between zones are compared in Fig. 5.
- The proposed BACC-RTE-SUC method generates a more uniform sound field without noticeable sacrifice in AC.

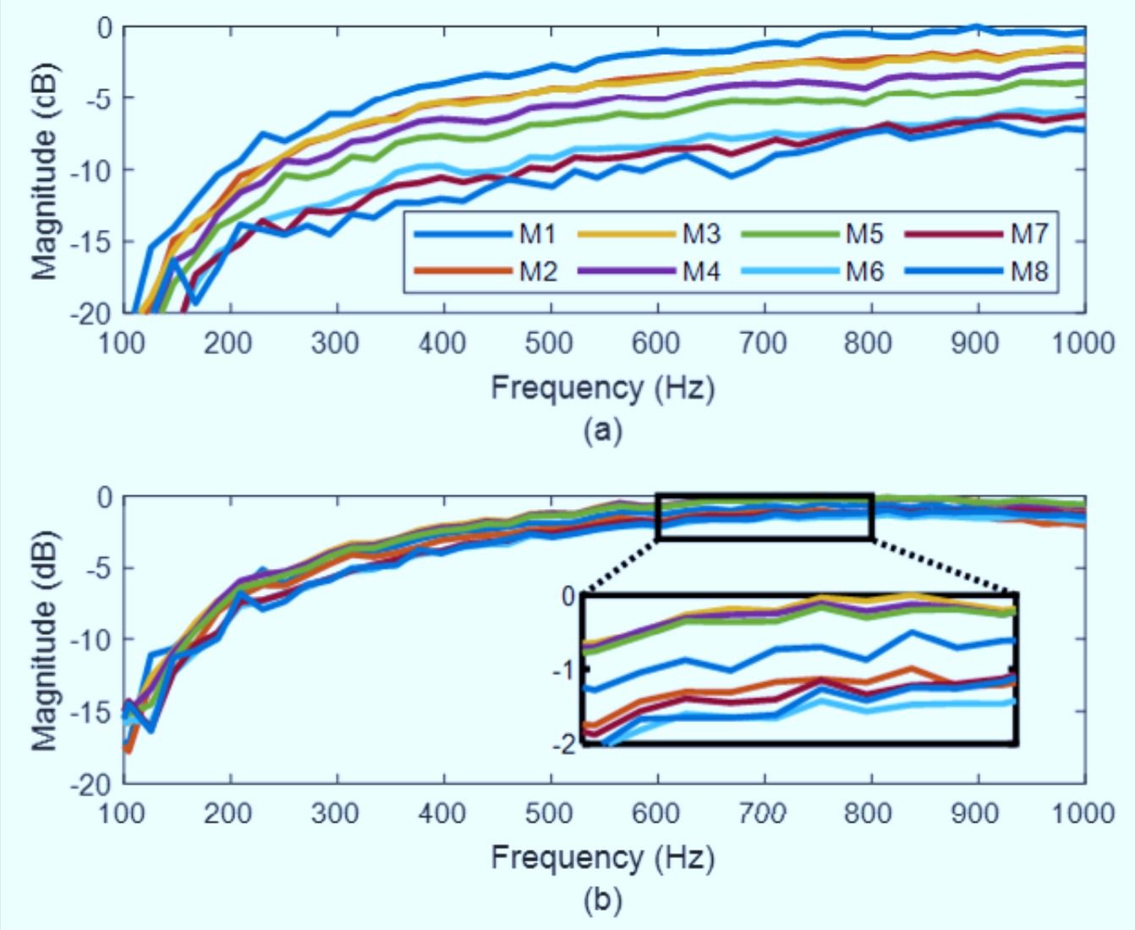

Fig. 3. Frequency responses at different microphones (M1-8) by (a) BACC-RTE and (b) BACC-RTE-SUC.

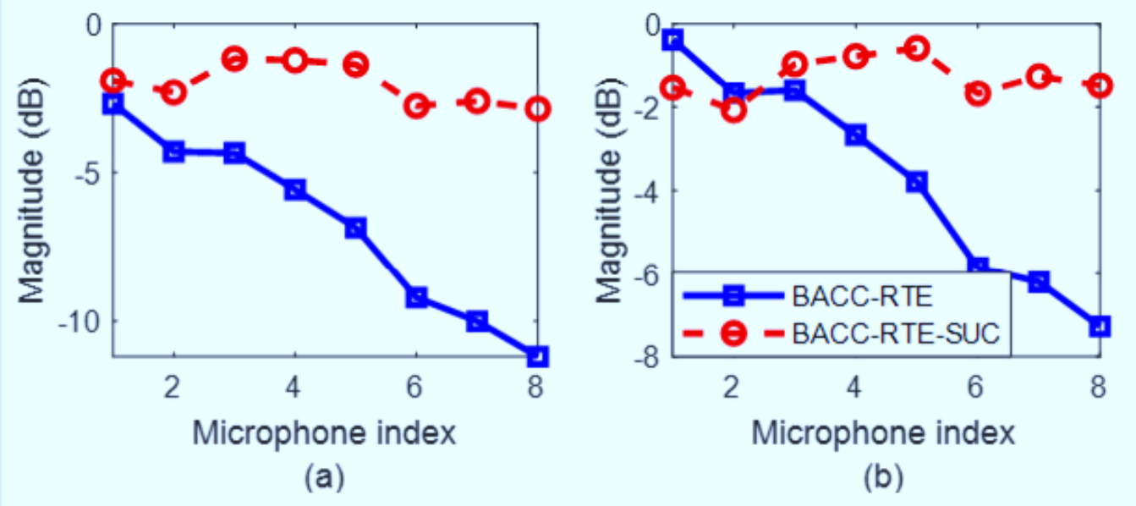

Fig. 4. Sound pressure magnitude at different microphones (M1-8) at (a) f = 500 Hz and (b) f = 1000 Hz.

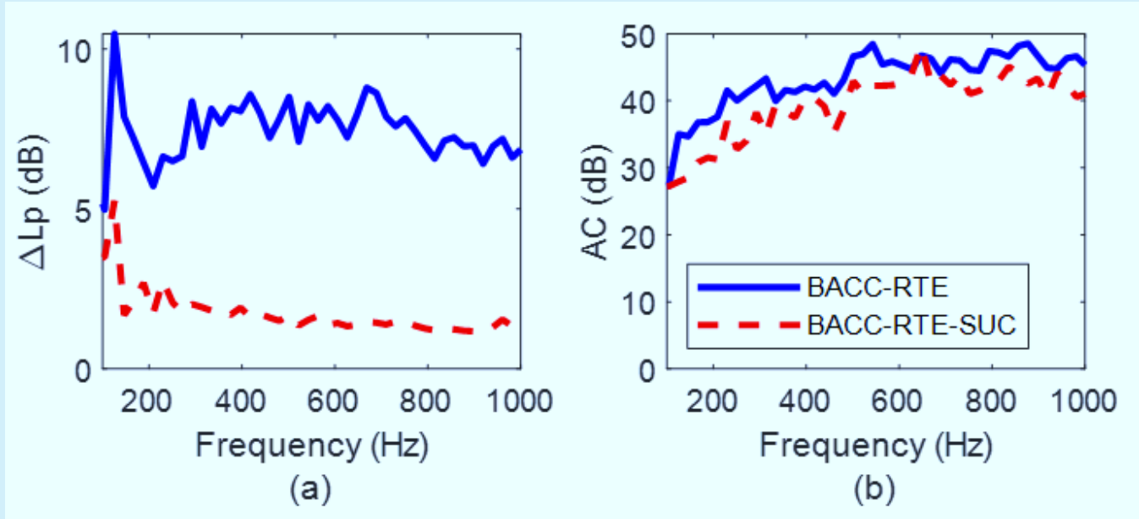

Fig. 5. Comparison of (a) the magnitude difference in the bright zone and (b) acoustic contrast between zones.

## Conclusions

- This paper proposes a spatial uniformity constraint for the sound pressure distribution in the bright zone and applies it in the time-domain broadband acoustic contrast control method.
- Simulations with measured room impulse responses demonstrate that the proposed method can effectively generate a more uniform sound field in the bright zone without noticeable impacts on the frequency responses in the bright zone and the acoustic contrast between zones.

## References

[1] Y. Cai, M. Wu, L. Liu and J. Yang, "Time-domain acoustic contrast control design with response differential constraint in personal audio systems," J. Acoust. Soc. Am., vol. 135, no. 6, pp. EL257, 2014.

[2] D. H. M. Schellekens, M. B. Moller, and M. Olsen, "Time domain acoustic contrast control implementation of sound zones for low-frequency input signals," in ICASSP, IEEE International Conference on Acoustics, Speech and Signal Processing – Proceedings, 2016, pp. 365-369.