

ACOUSTIC ECHO CANCELLATION BASED ON M-CHANNEL IIR COSINE-MODULATED FILTER BANK

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ABSTRACT

In this paper, an acoustic echo canceller (AEC) based on an M-channel infinite-impulse response (IIR) cosine-modulated filter bank (CMFB) with near-perfect reconstruction (PR) property is proposed. The use of a 2-channel lossless lattice section with 1st order allpass filter in the design of the prototype filter that is common to both the analysis and the synthesis filter banks permits the filter bank design to be simple and allows the prototype filter to have better stopband attenuation and sharper roll-off characteristics than that of previous designs of similar complexity. The effectiveness of AEC based on the proposed IIR CMFB is evaluated in terms of the echo return loss enhancement (ERLE).

1. INTRODUCTION

Hands-free communication system generally requires the use of an AEC to eliminate acoustic feedback from the loudspeaker to the microphone. The AEC adaptively estimates the room impulse response between the microphone and the loudspeaker and removes the acoustic echo from the microphone. Typically acoustic echo is on the order of few ten to hundred milliseconds long and requires long delay and high computational complexity in its estimation. For these reasons various methods have been proposed. One promising method that reduces computational load and improves performance is based on a subband structure [1]. An M-channel filter bank structure using M analysis and M synthesis filters, $\{H_i(z)\}_{i=0}^{M-1}$ and $\{F_i(z)\}_{i=0}^{M-1}$, respectively is shown in Fig. 1. With this kind of subband structure, the echo is reduced on a subband basis. But in order to use the subband structure for AEC, two factors must be considered. First the filter bank must have high stopband attenuation and subband discrimination to reduce aliasing since any aliasing that is induced by the decimation procedure degrades the performance of AEC. Second additional computation and system

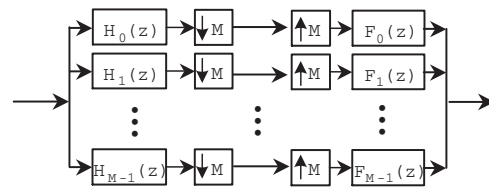


Fig. 1. Structure of M-channel filter bank

delay by the filter bank must be minimized. It is easier to satisfy the two factors with an IIR filter bank than with an FIR filter bank; however, the design of an IIR filter bank is much more difficult than that of an FIR filter bank. In fact no known M-channel IIR filter bank exists that performs satisfactorily for the AEC application. Various subband methods have been proposed in the past, but most have been based on either an FIR filter bank or a 2-channel IIR filter bank [2]. In this paper, a novel method for designing a prototype filter for M-channel IIR CMFB is proposed. The prototype filter is designed using simple design constraints on a small number of parameters. In the design method, a 2-channel IIR lossless lattice structure is used to simplify the design of the polyphase components of the IIR prototype filter. The lattice structure contains a number of 1st order allpass filter components. In this paper, the PR condition is relaxed to make the design simple and to reduce the number of parameters. The proposed structure achieves near PR.

The paper is organized as follows. Section 2 shows the theory of the proposed method for designing M-channel IIR CMFB. Section 3 presents the design procedure and design examples using the proposed method. Section 4 shows the simulation results for AEC using the designed CMFB. Finally, Section 5 concludes the paper.

2. PROPOSED M-CHANNEL IIR CMFB

The k^{th} impulse responses of the analysis and the synthesis filters, $h_k[n]$ and $f_k[n]$, are obtained from the analysis and

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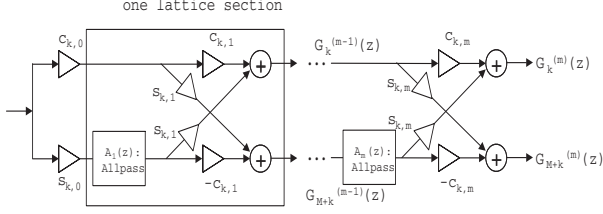


Fig. 2. 2-channel IIR lossless lattice structure ($c_{k,m} = \cos\theta_{k,m}$, $s_{k,m} = \sin\theta_{k,m}$)

the synthesis prototype filters, $h[n]$ and $f[n]$, as shown below

$$h_k[n] = 2h[n] \cos \left((2k+1) \frac{\pi}{2M} \left(n - \frac{D}{2} \right) + (-1)^k \frac{\pi}{4} \right) \quad (1)$$

$$f_k[n] = 2f[n] \cos \left((2k+1) \frac{\pi}{2M} \left(n - \frac{D}{2} \right) - (-1)^k \frac{\pi}{4} \right) \quad (2)$$

for $k = 0, 1, \dots, M-1$ where D is the overall system delay of the filter bank. The type I polyphase representation of prototype filters $H(z)$ and $F(z)$ can be expressed as

$$H(z) = \sum_{m=0}^{2M-1} z^{-m} G_m(z^{2M}), \quad (3)$$

$$F(z) = \sum_{m=0}^{2M-1} z^{-m} K_m(z^{2M}) \quad (4)$$

where $G_m(z^{2M})$ and $K_m(z^{2M})$ are type I polyphase components of $H(z)$ and $F(z)$. The constraint on $G_m(z^{2M})$ and $K_m(z^{2M})$ for PR is given in [3], but this PR condition with the causality and stability conditions of the filter makes the design complex. In order to simplify the design, some of these conditions are relaxed. By designing the analysis and synthesis filter bank from a common prototype filter, the passbands of $H_k(z)$ and $F_k(z)$ can coincide with one another. This relaxation gives near PR CMFB. To obtain $G_m(z^{2M})$ a two-channel IIR lossless lattice structure as shown in Fig. 2 is utilized for $k = 0, 1, \dots, M-1$. As shown in the figure, the k^{th} and $(M+k)^{\text{th}}$ pairs of the polyphase components $\{G_k^{(m)}(z), G_{M+k}^{(m)}(z)\}$ using m lattice sections are obtained from m numbers of 1st order allpass filters, $\{A_i\}_{i=1}^m$, and four-multiplier lattice sections, $\begin{bmatrix} \cos\theta_{k,i} & \sin\theta_{k,i} \\ \sin\theta_{k,i} & -\cos\theta_{k,i} \end{bmatrix}_{i=1}^m$. The relationship between pairs, $\{G_k^{(m)}(z), G_{M+k}^{(m)}(z)\}$ and $\{G_k^{(m-1)}(z), G_{M+k}^{(m-1)}(z)\}$ is given by the following recursive equation,

$$\begin{bmatrix} G_k^{(m)}(z) \\ G_{M+k}^{(m)}(z) \end{bmatrix} = \begin{bmatrix} \cos\theta_{k,m} & \sin\theta_{k,m} \\ \sin\theta_{k,m} & -\cos\theta_{k,m} \end{bmatrix} \cdot \begin{bmatrix} 1 & 0 \\ 0 & A_m(z) \end{bmatrix} \begin{bmatrix} G_k^{(m-1)}(z) \\ G_{M+k}^{(m-1)}(z) \end{bmatrix} \quad (5)$$

for $m \geq 1$, $0 \leq k \leq M-1$

where

$$G_k^0 = \cos\theta_{k,0}, \quad G_{M+k}^0 = \sin\theta_{k,0}, \quad (6)$$

$$A_m(z) = \frac{a_m + z^{-1}}{1 + a_m z^{-1}}, \quad |a_m| < 1. \quad (7)$$

By requiring $|a_m| \leq 1$, the stability condition is easily met and by the use of lattice structure, the order of polyphase component can be incremented arbitrarily. The polyphase component matrix $\mathbf{E}(z)$ that is defined as

$$\mathbf{E}(z) \equiv \begin{bmatrix} \mathbf{g}_0(z^{2M}) \\ z^{-M} \mathbf{g}_1(z^{2M}) \end{bmatrix} \quad (8)$$

where

$$\mathbf{g}_0(z) \equiv \text{diag}[G_0(-z), \dots, G_{M-1}(-z)] \quad (9)$$

$$\mathbf{g}_1(z) \equiv \text{diag}[G_M(-z), \dots, G_{2M-1}(-z)] \quad (10)$$

and is derived from the given lattice structure has the lossless property, that is, $\tilde{\mathbf{E}}(z)\mathbf{E}(z) = \mathbf{I}_M$. $\tilde{\mathbf{E}}(z)$ represents the tilde notation of $\mathbf{E}(z)$. A synthesis bank such that the overall analysis/synthesis system satisfies PR can always be found from $\tilde{\mathbf{E}}(z)$ in the case of FIR filter bank [4]. Instead of deriving the synthesis prototype filter from $\tilde{\mathbf{E}}(z)$ which will make it unstable, the prototype of analysis filter $h[n]$ is used as the prototype of synthesis ($f[n] = h[n]$).

3. DESIGN OF PROPOSED M-CHANNEL IIR CMFB AND DESIGN EXAMPLES

In order to obtain an M-channel IIR CMFB, the IIR prototype filter must be designed. The design procedure requires a parameter optimization process. For this, the parameters must be initialized first.

3.1. Initialization

The parameters of the IIR prototype filter are initialized as the follows

$$\theta_{k,m} = \begin{cases} \frac{\pi}{4}, & m = 0 \\ \frac{\pi}{2}, & m \neq 0 \end{cases} \quad \text{for } 0 \leq k \leq M-1, \quad (11)$$

$$a_m = \{a : \text{real value}, |a| < 1\}. \quad (12)$$

The initialization for $\theta_{k,m}$ is similar to that of optimization of FIR CMFB [4].

3.2. Optimization

After the parameters are initialized, they are optimized to minimize the objective functions Φ_1 and Φ_2 given below

$$\Phi_1 = \int_{\pi/2M+\delta}^{\pi} |H(e^{j\omega})|^2 d\omega, \quad (13)$$

$$\Phi_2 = \max_{\omega \in [\pi/2M+\delta, \pi]} |H(e^{j\omega})| \quad (14)$$

where $\delta < \frac{\pi}{2M}$. The parameters \mathbf{P} of the analysis prototype filter $H(z)$ can be obtained by iteratively minimizing Φ_1 and Φ_2 subjected to $|a_k| < 1$, for $k = 1, \dots, m$. This constraint is necessary for the stability of the designed prototype filter. Φ_1 represents the stopband energy and Φ_2 the maximum value in the stopband of the prototype filter. The minimization of Φ_2 after Φ_1 has the effect of lowering the stopband attenuation and making it equiripple.

3.3. Examples

Using the proposed method, a 4-channel IIR prototype filter with $m = 1$ is obtained. The magnitude response of the designed prototype filter is shown in Fig. 3.

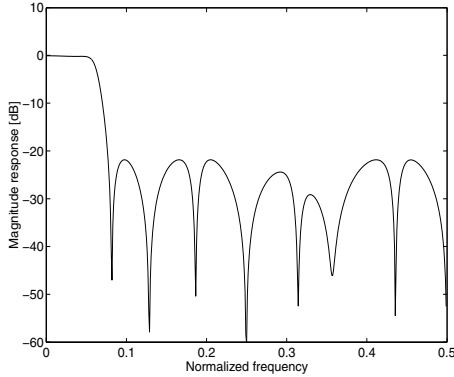


Fig. 3. Magnitude response of 4-channel IIR prototype filter ($m = 1$)

The orders of numerator and denominator of this prototype filter are 15 and 8, respectively. The filter characteristics can be improved using more lattice sections in the design. The magnitude response of the designed IIR prototype filter using $m = 4$ is shown in Fig. 4. The orders of numerator and denominator of the filter are 39 and 32 respectively and the number of taps is 45. The IIR prototype filter which is designed by the proposed method has approximately -53 dB stopband attenuation. The 4-channel IIR CMFB obtained by using the designed prototype filter in Fig. 4 is shown in Fig. 5.

For comparison, the magnitude response of the 4-channel PR IIR CMFB of similar complexity (43-tap) using the method

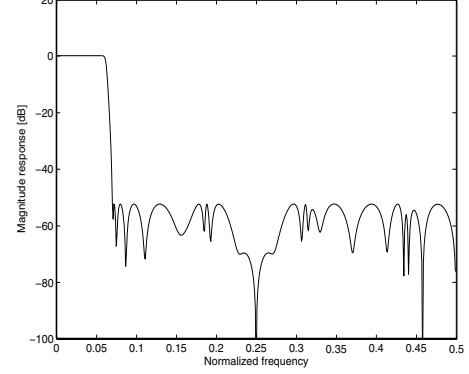


Fig. 4. Magnitude response of 4-channel IIR prototype filter ($m = 4$)

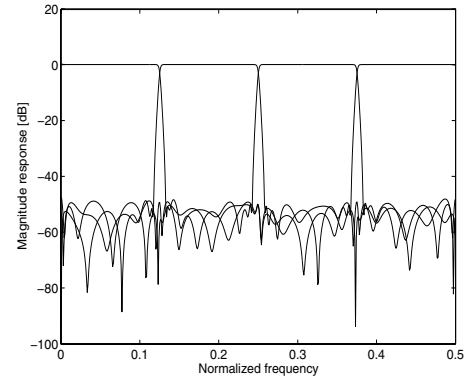


Fig. 5. Magnitude response of 4-channel IIR analysis CMFB ($m = 4$)

proposed by Mao et al. is shown in Fig. 6 [5]. It can be seen that the IIR analysis filters using the proposed method has about 24 dB higher stopband attenuation and sharper roll-off characteristics than the analysis filters of similar complexity proposed by Mao et al.

To see the distortion of the filter bank, the plot of overall transfer function $T(z)$ which is expressed as

$$T(z) = \frac{1}{M} \sum_{k=0}^{M-1} H_k(z) F_k(z) \quad (15)$$

is shown in Fig. 7. From this figure, near PR is observed.

4. APPLICATION TO ACOUSTIC ECHO CANCELLATION

The proposed 4-channel IIR CMFB and PR IIR CMFB proposed by Mao et al. are applied to AEC. The room impulse response between the loudspeaker and the microphone is made to have its length of 500 samples. In AEC, normalized least mean-square (NLMS) algorithm with step-size 0.5

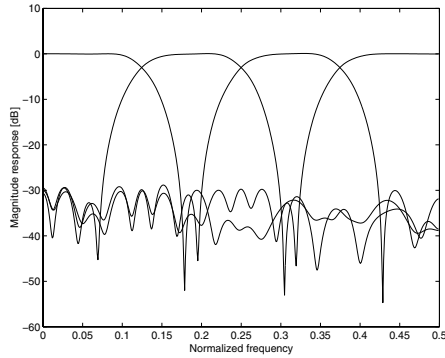


Fig. 6. Magnitude response of 4-channel PR IIR analysis CMFB of similar complexity (43-tap)

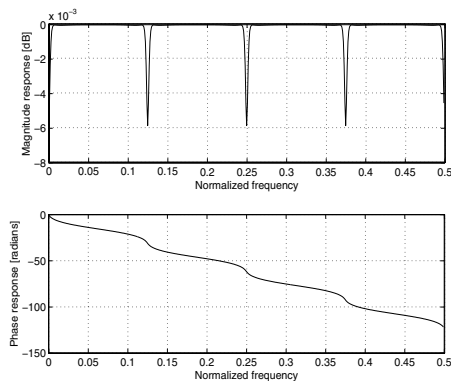


Fig. 7. Reconstruction quality of the filter bank

was used. A set of AEC simulation is conducted with various speech signals which are sampled at 8KHz. The performances of the subband AEC using both the proposed 4-channel IIR CMFB and the PR IIR CMFB proposed by Mao et al. are evaluated in terms of ERLE which is defined as

$$ERLE \equiv 10 \log \frac{E[d[n]^2]}{E[e[n]^2]} \quad (16)$$

where $d[n]$ is the echo signal and $e[n]$ is the residual echo signal. The performances of the subband AEC using the 4-channel IIR CMFB and PR IIR CMFB of similar complexity are shown in Fig. 8 as average values for 80 speech signals. From Fig. 8, it can be verified that the subband AEC using IIR CMFB has about 27 dB maximum average ERLE, which is 12 dB higher than using PR IIR CMFB of similar complexity. The result shows that the proposed M-channel IIR CMFB is more effective in AEC application than PR IIR CMFB.

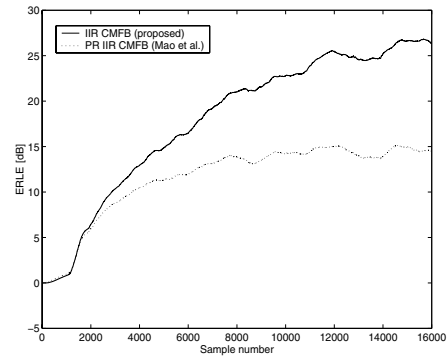


Fig. 8. Average ERLE of subband AEC using 4-channel IIR and PR IIR CMFB for 80 speech signals

5. CONCLUSION

An AEC based on an M-channel IIR CMFB with near PR is proposed. We can design the IIR filter bank easily using a number of lattice sections with 1^{st} order allpass filter components. Design examples show that the proposed IIR CMFB has higher stopband attenuation and sharper roll-off than Mao's PR IIR CMFB of similar complexity. The two filter banks are applied to subband AEC respectively. The simulation result shows that AEC using the proposed M-channel IIR CMFB is more effective than using Mao's PR IIR CMFB of similar complexity in AEC application.

6. REFERENCES

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