Highly selective M-channel IIR cosine-modulated filter banks

S.G. Kim and C.D. Yoo

A simple method for designing highly selective M-channel infinite-impulse response (IIR) cosine-modulated filter banks (CMFBs) is proposed. High selectivity is achieved by relaxing the perfect reconstruction condition. The proposed method is simple because the design is based on a two-channel lattice structure with first-order allpass filters.

Introduction: A highly selective critically sampled filter bank is required to reduce interband aliasing effects in subband adaptive filtering applications that also require low computational load [1]. It is generally known that infinite-impulse response (IIR) filters have higher stopband attenuation and sharper roll-off with lower system delay than finite-impulse response (FIR) filters of similar complexity; however, their designs are generally more complicated than those of FIR filters since they require more design constraints and parameters [2]. Therefore, IIR filter bank designs are generally limited to the two-channel case [2, 3].

Methods for designing M-channel IIR perfect reconstruction (PR) cosine-modulated filter banks (CMFBs) have recently been reported [4–6]. However, these methods were found to be unsatisfactory in subband adaptive filtering applications such as acoustic echo cancellation: (i) their design methods are complex; (ii) the PR CMFB designed by these methods requires high computational load and has a wide transition bandwidth which leads to high interband aliasing.

To reduce interband aliasing such that it is more suitable for subband adaptive filtering applications, a novel method for designing highly selective M-channel IIR CMFBs is proposed. The proposed method is simple since the design is based on a two-channel IIR cascaded lattice structure, in which each stage is composed of a first-order allpass filter and four multipliers. For the prototype filter of the CMFB to have higher stopband attenuation and sharper roll-off characteristic than the PR case, the linear-phase condition for PR is relaxed. The phase distortion that appears as a result of relaxation can be compensated by various techniques [1, 7]. If the application is in speech, phase distortion may not be critical, since the human auditory system is relatively insensitive to phase distortion.

Theory: The analysis and synthesis filters of the CMFB system are obtained by cosine modulation of the real coefficient prototype filter. The cosine modulation simplifies the design procedure and obtains an efficient implementation. The impulse responses of the kth analysis and synthesis filters, $h_k[n]$ and $f_k[n]$, are cosine-modulated versions of the impulse response of the IIR prototype filter $h[n]$. Namely, they are given as

$$h_k[n] = 2h[n]\cos\left(\frac{\pi}{M}(k+0.5)\left(n-\frac{L}{2}\right)+(-1)^k\frac{\pi}{4}\right) \qquad (1)$$

$$f_k[n] = 2h[n]\cos\left(\frac{\pi}{M}(k+0.5)\left(n-\frac{L}{2}\right)-(-1)^k\frac{\pi}{4}\right) \qquad (2)$$

for $k=0, 1, \ldots, M-1$, where L is the order of the numerator of the prototype filter. The impulse responses $h_k[n]$ and $f_k[n]$ are similar to the FIR CMFB case: we have assumed that all the analysis and synthesis filters share the same denominator and the numerator of the overall transfer function is linear-phase [8].

Let the IIR prototype filter be

$$H(z) = \sum_{k=0}^{2M-1} z^{-k} P_k(z^{2M}) \qquad (3)$$

where $P_k(z)$ is kth type-I polyphase components of $H(z)$. We assume that $P_k(z)=N_k(z)/D(z)$ for $k=0, 1, \ldots, 2M-1$. In general, for a PR CMFB, the following condition must be satisfied,

$$P_k(z)P_{2M-k-1}(z) + P_{M+k}(z)P_{M-k-1}(z) = c\cdot(-z)^{-s} \qquad (4)$$

where c and s are constants: s determines the overall system delay [4–6]. For simplicity, M is assumed to be even. Similar results can also be derived when M is odd. The overall transfer function using the polyphase components which satisfies (4) is given as $c\cdot z^{-d}$ where d is the overall system delay. However, a CMFB which satisfies the above PR condition does not achieve sharp roll-off characteristic.

In this Letter, in order to design a highly selective M-channel IIR CMFB for subband adaptive filtering, the PR condition of (4) is relaxed as follows

$$P_k(z)P_{2M-k-1}(z) + P_{M+k}(z)P_{M-k-1}(z) = c\cdot z^{-m}\frac{\tilde{D}(z)}{D(z)} \qquad (5)$$

where m is the order of the numerators of the polyphase components. The tilde notation of $D(z)$ is defined such that $\tilde{D}(z)=D_*(z^{-1})$, where the asterisk ($*$) in a subscript denotes the conjugate of coefficients. The delay term of the right-hand side of (4) is replaced with an allpass filter. The overall transfer function of the CMFB which satisfies the condition (5) is represented as

$$c\cdot z^{-L}\frac{\tilde{D}(-z^{2M})}{D(-z^{2M})} \qquad (6)$$

Since $z^{-L}\tilde{D}(-z^{2M})/D(-z^{2M})$ is also an allpass filter, the magnitude response of the overall transfer function is a constant and the phase response is governed by the allpass filter. We can express (5) as

$$P_k(z)\tilde{P}_k(z) + P_{M+k}(z)\tilde{P}_{M+k}(z) = c \qquad (7)$$

since the numerator of $H(z)$ is designed to be linear-phase so that the numerator $N_k(z)$ of the $P_k(z)$ satisfies the following relationship

$$N_k(z) = z^{-m}\tilde{N}_{2M-k-1}(z) \qquad (8)$$

for $k=0, 1, \ldots, M-1$. This relationship approximately reduces the number of total parameters by a half.

Two-channel lattice structure: Any polyphase component pair that satisfies the condition (7) can be realised using a two-channel cascaded lattice structure shown in Fig. 1 for $k=0, 1, \ldots, M/2-1$. The proposed lattice structure is obtained by replacing z^{-1} of the FIR lossless lattice structure with a first-order allpass filter [8]. Let $\{P_k^{(m)}(z), P_{M+k}^{(m)}(z)\}$ be the transfer functions from the input to the output of the mth section of the kth lattice structure. The relationship between $\{P_k^{(m)}(z), P_{M+k}^{(m)}(z)\}$ and $\{P_k^{(m-1)}(z), P_{M+k}^{(m-1)}(z)\}$ is given by the following recursive equation

$$\begin{bmatrix} P_k^{(m)}(z) \\ P_{M+k}^{(m)}(z) \end{bmatrix} = \begin{bmatrix} \cos\theta_{k,m} & \sin\theta_{k,m} \\ \sin\theta_{k,m} & -\cos\theta_{k,m} \end{bmatrix}\begin{bmatrix} P_k^{(m-1)}(z) \\ A_m(z)P_{M+k}^{(m-1)}(z) \end{bmatrix} \qquad (9)$$

where

$$A_m(z) = \frac{a_m + z^{-1}}{1+a_m z^{-1}} \qquad (10)$$

for $m\geq 1$ and $k=0, 1, \ldots, M/2-1$. The lattice transfer functions are initialised as

$$P_k^0 = \cos\theta_{k,0} \quad \text{and} \quad P_{M+k}^0 = \sin\theta_{k,0} \qquad (11)$$

for $k=0, 1, \ldots, M/2-1$. To satisfy the condition that all the polyphase components have the same denominator $D(z)$, the same set of the allpass filters $\{A_i(z)\}_{i=1}^m$ must be used in all the lattice structures. The M-channel IIR prototype filter can be easily designed by following the design steps proposed in [8]. In addition, it is required that $|a_i|<1$ for $i=1, 2, \ldots, m$ during the optimisation procedure for the stability of the IIR prototype filter. This constrained nonlinear optimisation problem can be easily solved using the constrained nonlinear optimisation subroutine in MATLAB. The use of the two-channel IIR lattice structure in the design of the polyphase components makes the design simple and its implementation efficient.

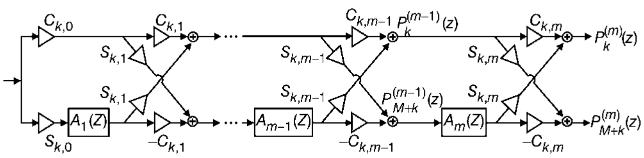

Fig. 1 *Two-channel cascaded IIR lattice structure for design of $P_k(z)$ and $P_{M+k}(z)$ ($c_{k,m}=\cos\theta_{k,m}$, $s_{k,m}=\sin\theta_{k,m}$)*

Results: The magnitude response of the designed 16-channel IIR CMFB using the proposed method is shown in Fig. 2 using four sections per two-channel lattice. The stopband attenuation of each filter of the CMFB is about 42 dB and the normalised transition bandwidth (NTB) is 0.0019. In the four-channel case, the stopband attenuation and the NTB of the proposed CMFB using four sections per two-channel lattice are 10 dB higher and 0.0944 narrower than those of the PR CMFB of similar complexity proposed by Mao *et al.* [4]. The proposed CMFB is more suitable for subband adaptive filtering than the PR CMFB proposed by Mao. It is important to point out that the magnitude response of the overall transfer function of the designed CMFB is constant and the phase response is almost linear except at band edges.

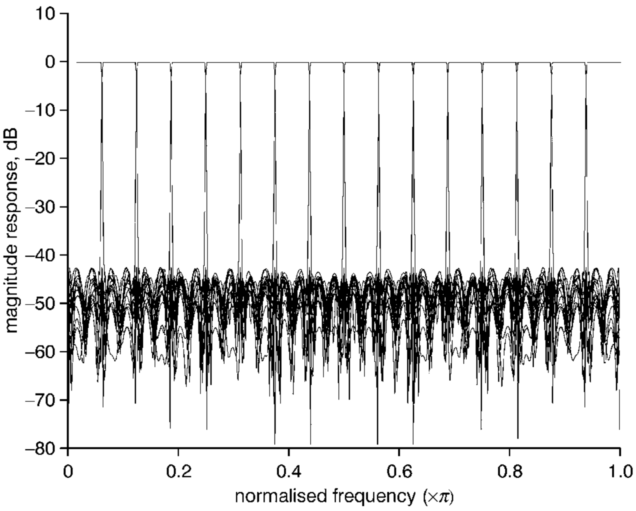

Fig. 2 *Magnitude response of proposed 16-channel IIR CMFB*

Conclusion: Based on the two-channel IIR lattice structure, a simple method for designing a highly selective *M*-channel IIR CMFB is proposed. Efficient implementation is possible using the lattice structure. The relaxation of PR property allows the IIR CMFB to be highly selective with relatively low complexity. The proposed IIR CMFB can be conducive for subband adaptive filtering applications that require low complexity.

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S.G. Kim and C.D. Yoo (*Department of Electrical Engineering and Computer Science, Korea Advanced Institute of Science and Technology, Guseong-dong, Yooseong-gu, Daejon, Republic of Korea*)

E-mail: zom@eeinfo.kaist.ac.kr

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