and the proposed SCS. The disk rotational speed is 5000rpm. Fig. 2*a* represents a track cross signal that is generated as the beam spot passes along the tracks. Fig. 2*b* and *c* show v_r and v_m, respectively. Although v_r becomes zero, i.e. the beam spot arrives at the target track, v_e due to the effect of v_d remains larger than the allowable velocity error bound of 6mm/s. In this case, the track-following servo system to read the desired information should wait until v_e is within the allowable limit. During the waiting period, however, the beam spot has already deviated several tracks from the target track, as shown in Fig. 2*a*. Therefore, after the track number on which the beam spot rests is read, the beam spot should be moved by the difference between the target track and the current track. Such repeated seek operations add significant delay to the total access time.

Table 1: Comparison of performance between conventional and proposed SCS

Jump track number [track]	500	6000	9000
Conventional SCS [ms]	43	84	104
Proposed SCS [ms]	15	56	76

Based on 24× CD-ROM

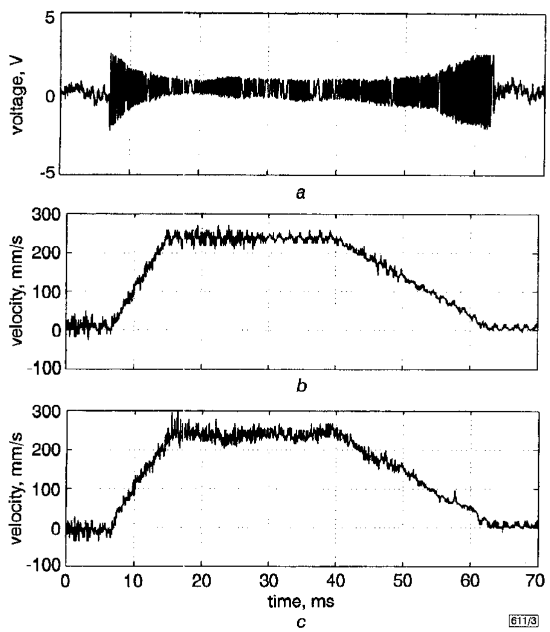

Fig. 3 *Experimental results using proposed SCS*

a Track cross signal
b Reference velocity
c Measurable velocity

When the proposed SCS and designed controllers are used, however, v_m follows v_r exactly because the fine actuator rejects the effect of v_d on v_m as shown in Fig. 3. As a result, without waiting and repeated seek, the track-following servo system starts to read the desired information as soon as the seek operation ends - the beam spot reaches the target track.

Therefore, it can be concluded that the proposed SCS satisfies the control objective, i.e. short access time, even for high-speed rotational ODDs. Table 1 shows the average access time when the conventional SCS and the proposed SCS are applied to a 24× CD-ROM. In the proposed SCS, we can obtain such results because the waiting time and the repeated seek time of the conventional SCS is reduced.

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References

1 SUZUKI, M., TANKA, H., and MIURA, Y.: 'Pull-in condition and method of tracking servo in optical disk drive', *J. Inst. Tele. Jpn.*, 1990, **44**, (10), pp. 1391–1397

2 ZHOU, K., DOYLE, J.C., and GLOVER, K.: 'Robust and optimal control' (Prentice-Hall, Inc., 1996)

Low-complexity, perfect reconstruction FIR QMF bank

Sau-Gee Chen and Min-Chi Kao

A low-complexity, perfect reconstruction quadrature mirror filter (QMF) bank is proposed, which requires only 50% of the multiplications and additions of the existing QMF banks per output sample. In addition, the new QMF bank only needs to solve a set of linear equations instead of the commonly required nonlinear optimisation technique for the prototype filter.

Introduction: Fig. 1 shows a two-channel quadrature mirror filter (QMF) bank in which $H_0(z)$ and $H_1(z)$ are the analysis filters, and $G_0(z)$ and $G_1(z)$ are the synthesis filters [1, 2]. The earliest QMF bank [3] chooses the analysis filter pair as $H_1(z) = H_0(-z)$. However, this type is only approximately perfect reconstruction (PR). The second type is the paraunitary PR QMF bank [2]. Based on the factorisation of a half-band filter $H_{hb}(z) = H_0(z)\tilde{H}_0(z)$ where $\tilde{H}_0(z)$ is the maximum phase mirror of an odd-order N–1 filter $H_0(z)$, the analysis filters form a power complementary pair as related by $H_1(z) = -z^{-(N-1)}\tilde{H}_0(-z)$. However, all the filters are nonlinear-phase. Besides, PR cannot be guaranteed when the quantisation errors are introduced. To alleviate these drawbacks, Vaidyanathan proposed the linear-phase PR QMF lattice [2, 4]. However, this requires an initial guess of the lattice parameters for optimisation, and has a greater number of additions than do the former QMF banks. All the mentioned QMF banks have a long reconstruction delay of N–1.

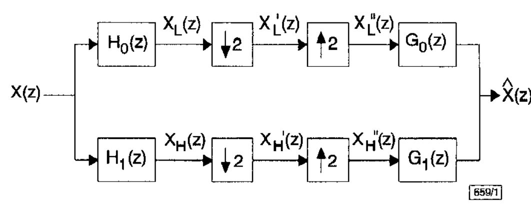

Fig. 1 *Two-channel QMF bank*

An (N–1)th-order half-band FIR filter satisfies $H_{hb}(z) - H_{hb}(-z) = z^{(N-1)/2}$. The half-band filter is important in the design of sharp transition FIR filters, due to its low complexity (~50% of the filter coefficients are zero), and mirror image property (the filter automatically has a good stopband response if it has a good passband response). Intuitively, the strictly complementary filters $[H_{hb}(z), z^{(N-1)/2} - H_{hb}(z)]$ would be a good QMF analysis filter pair. However, this pair cannot achieve PR.

This Letter proposes a new half-band based, low-complexity PR QMF bank, which has a lower reconstruction delay of D+(N–1)/2, D < (N–1)/2, than the N–1 delay of all the previously mentioned QMF banks. More importantly, the PR QMF bank has a complexity less than half those of prior QMF banks. Simulations are conducted to test the performance of the PR QMF bank.

New low-complexity PR QMF bank: For a QMF bank, the output is given by

$$\begin{aligned}\hat{X}(z) &= \frac{1}{2}[H_0(z)G_0(z) + H_1(z)G_1(z)]X(z)\\ &+ \frac{1}{2}[H_0(-z)G_0(z) + H_1(-z)G_1(z)]X(-z)\\ &= F_0(z)X(z) + F_1(z)X(-z) \qquad (1)\end{aligned}$$

A sufficient condition for alias cancellation is $G_0(z) = 2H_1(-z)$ and $G_1(z) = -2H_0(-z)$. Hence, the overall transfer function for the aliasfree QMF bank is

$$F_0(z) = H_0(z)H_1(-z) - H_0(-z)H_1(z) \qquad (2)$$

Let $P(z) = H_0(z)H_1(-z)$. For PR, $P(z)$ is required to be a half-band filter.

For the realisation of a low-complexity PR QMF bank, let $H_0(z)$ be a half-band linear-phase FIR filter of order N–1, and

$$H_1(z) = z^{-D} - H_0(z) \qquad (3)$$

where the variable D is to be determined. Substituting eqn. 3 into eqn. 2, we obtain

$$\begin{aligned} F_0(z) &= H_0(z)[(-z)^{-D} - H_0(-z)] - [z^{-D} - H_0(z)]H_0(-z) \\ &= z^{-D}[(-1)^{-D}H_0(z) - H_0(-z)] \end{aligned} \qquad (4)$$

Thus, to achieve PR, i.e. $F_0(z) = z^{-(D+(N-1)/2)}$, D is required to be an even number. As a result, the proposed PR QMF bank achieves a lower reconstruction delay of $D + (N-1)/2$, $D < (N-1)/2$, than the N–1 delay of all the previously mentioned QMF banks. Note that D cannot be $(N-1)/2$, because $(N-1)/2$ is odd.

Optimisation of prototype filter: A much simpler one-shot optimisation technique than those of the mentioned QMF banks is proposed as follows. It only needs to solve a set of linear equations once for all without further iteration. First, note that if the stopband response of the half-band filter $|H_0(e^{j\omega})|$ is sufficiently small, then its passband response is automatically sufficiently close to unity as well. On the other hand, $|H_1(e^{j\omega})|^2$ can be shown to be

$$|H_1(e^{j\omega})|^2 = 1 - e^{-jD\omega}H_0(e^{-j\omega}) - e^{jD\omega}H_0(e^{j\omega}) + |H_0(e^{j\omega})|^2 \qquad (5)$$

In the stopband $\omega_s < \omega < \pi$, the higher-order term $|H_0(e^{j\omega})|^2$ is negligible compared with the other two terms, if the frequency response of $|H_0(e^{j\omega})|$ is sufficiently attenuated in that band. Accordingly, the fourth-order objective function E:

$$E \equiv \frac{1}{2\pi}\left\{\alpha_1\left(\int_0^{\omega_p}|H_1(e^{j\omega})|^2 d\omega + \alpha_{s1}\int_{\omega_s}^{\pi}\left||H_1(e^{j\omega})|^2 - 1\right|^2 d\omega\right) + \alpha_{s0}\int_{\omega_s}^{\pi}|H_0(e^{j\omega})|^2\, d\omega\right\} \qquad (6)$$

can be reduced to a second-order form as

$$E = \frac{1}{2\pi}\left\{\alpha_1\left(\int_0^{\omega_p}|H_1(e^{j\omega})|^2 d\omega + \alpha_{s1}\int_{\omega_s}^{\pi}|e^{-jD\omega}H_0(e^{-j\omega}) + e^{jD\omega}H_0(e^{j\omega})|^2 d\omega\right) + \alpha_{s0}\int_{\omega_s}^{\pi}|H_0(e^{j\omega})|^2\, d\omega\right\} \qquad (7)$$

where the αs are the weighting factors, and α_{s0} is relatively larger than the other two. The zero gradient of E will yield the required set of linear equations for the optimal least-squares filter.

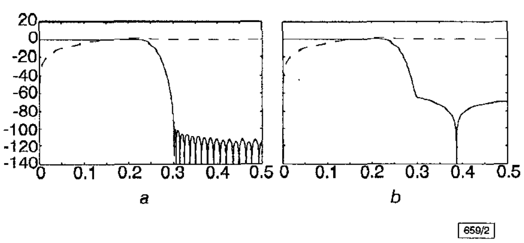

Fig. 2 *Magnitude responses for new PR QMF filter pair*

a $\alpha_{s0} = 10^6$
b $\alpha_{s0} = 10^3$

Design example: A filter pair $[H_0(z), H_1(z)]$ with $N = 63$, $D = 30$, $\omega_p = 0.4\pi$, $\omega_s = 0.6\pi$, $\alpha_1 = 1$, $\alpha_{s1} = 1$, and $\alpha_{s0} = 10^6$ was designed. Fig. 2 shows the magnitude responses of the resulting analysis filters. As shown in this Figure, $H_0(z)$ has a good stopband attenuation and a sharp transition. $H_1(z)$ exhibits a better response at the cost of a larger D up to $(N-3)/2$ and a longer delay up to N–2. Note that $H_0(z)$ is linear-phase, while $H_1(z)$ is nonlinear-phase and has a poorer response than that of $H_0(z)$. However, simulations [1] showed that the new QMF bank performs well. To further increase the stopband attenuation of $H_1(z)$ is left for future research. One feasible approach is to apply the lifting technique [5] to $H_1(z)$, at the cost of extra complexity.

Table 1: Complexity comparisons among new and previous QMF bank designs for analysis filtering

	Johnston's QMF	Conjugate QMF	Vaidyanathan's lattice	New QMF
Phase response	H_0 linear H_1 linear	H_0 nonlinear H_1 nonlinear	H_0 linear H_1 linear	H_0 linear H_1 nonlinear
MPUs	$N/4$	$N/2+1$ (lattice form)	$N/4+1$	$(N+1)/8$
APUs	$N/2$	$N/2$	$3N/4+1$	$(N+3)/4$

Polyphase realisation and complexity: Owing to the use of the half-band filter, the computational complexity of the proposed QMF bank is lower than those of the previous attempts. Its polyphase realisation and complexity analysis are described as follows. In type 1 polyphase representation, $H_0(z)$ can be written as

$$H_0(z) = H_{00}(z^2) + 0.5z^{-(N-1)/2} \qquad (8)$$

Since $H_{00}(z)$ is symmetric, its complexities can be further reduced. The input $X(z)$ and lower band output $X_L(z)$ after the analysis filtering are

$$\begin{aligned} X(z) &= X_0(z^2) + z^{-1}X_1(z^2) \\ X_L(z) &= [H_{00}(z^2) + 0.5z^{-(N-1)/2}][X_0(z^2) + z^{-1}X_1(z^2)] \end{aligned} \qquad (9)$$

Then, the lower band output after the decimation can be shown to be

$$X'_L(z) = X_L(z) \downarrow 2 = X_0(z)H_{00}(z) + 0.5z^{-(N+1)/4}X_1(z) \qquad (10)$$

Similarly, the upper band output after the decimation can be shown to be

$$X'_H(z) = X_H(z) \downarrow 2 = z^{-D/2}X_0(z) - X'_L(z) \qquad (11)$$

which costs no multiplication. Overall, only $(N+1)/8$ multiplications and $(N+3)/4$ additions are needed for each output pair of analysis filtering, which is about half those of the prior attempts. Table 1 summarises the complexity comparisons among the new and previous QMF bank designs.

Conclusion: A half-band based PR QMF bank was proposed. The optimisation of the design methodology is very simple. An advantage of this new QMF bank is the significant reduction in the number of multiplications and additions. Moreover, the proposed QMF bank has a lower reconstruction delay than those of the previous QMF banks.

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References

1 CHEN, S.O., KAO, M.C., and CHEN, S.P.: 'A new type of perfect-reconstruction QMF banks'. Proc. Asilomar Conf. on Signals, Systems and Computers, 1997, pp. 1334–1338

2 VAIDYANATHAN, P.P.: 'Multirate systems and filter banks' (Prentice-Hall, 1993)

3 JOHNSTON, J.D.: 'A filter family designed for use in quadrature mirror filter banks'. Proc. ICASSP, 1980, pp. 291–294

4 NGUYEN, T.Q., and VAIDYANATHAN, P.R.: 'Two-channel perfect-reconstruction FIR QMF structures which yield linear-phase analysis and synthesis filters', *IEEE Trans. Acoust. Soeech Signal Process.*, 1989, **ASSP-37**, (5), pp. 676–690

5 SWELDENS, W.: 'The lifting scheme: A custom-design construction of biorthogonal wavelets', *J. Appl. Comput. Harmonic Anal.*, 1996, **3**, (2), pp. 186–200