and the proposed SCS. The disk rotational speed is 5000rpm. Fig. 2a represents a track cross signal that is generated as the beam spot passes along the tracks. Fig. 2b and c show $v_t$ and $v_{scs}$ respectively. Although $v_t$ becomes zero, i.e., the beam spot arrives at the target track, $v_{scs}$ due to the effect of $v_t$ 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 $v_t$ 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. 2a. 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

<table>
<thead>
<tr>
<th>Jump track number [track]</th>
<th>Conventional SCS [ms]</th>
<th>Proposed SCS [ms]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>500</td>
<td>600</td>
</tr>
<tr>
<td></td>
<td>9000</td>
<td>9000</td>
</tr>
<tr>
<td>Conventional SCS [ms]</td>
<td>43</td>
<td>84</td>
</tr>
<tr>
<td>Proposed SCS [ms]</td>
<td>15</td>
<td>56</td>
</tr>
</tbody>
</table>

Based on 24x 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, $v_{scs}$ follows $v_t$ exactly because the fine actuator rejects the effect of $v_t$ on $v_{scs}$ 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 24x 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.

References


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 $H_b(z)$ and $H_g(z)$ are the analysis filters, and $G_b(z)$ and $G_g(z)$ are the synthesis filters [1, 2]. The earliest QMF bank [3] chooses the analysis filter pair as $H_b(z) = H_g(z^2)$. 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 $H_b(z) = H_d(z)H_m(z)$ where $H_d(z)$ is the maximum phase mirror of an odd-order $N-1$ filter $H_m(z)$, the analysis filters form a power complementary pair as related by $H_b(z) = z^{N-1}H_d(z)$. However, all the filters are non-linear-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 $H_b(z) - H_g(z^2) = z^{N-1}H_d(z)$. 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 $[H_d(z), \ z^{N-1}H_d(z)]$ 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

$$\hat{x}(z) = \frac{1}{2} [H_b(z)G_b(z) + H_g(z)G_g(z)]X(z)$$
$$+ \frac{1}{2} [H_b(-z)G_b(z) + H_g(-z)G_g(z)]X(-z)$$
$$= F_0(z)X(z) + F_1(z)X(-z)$$

A sufficient condition for alias cancellation is $G_b(z) = 2H_b(-z)$ and $G_g(z) = -2H_g(-z)$. Hence, the overall transfer function for the alias-
free QMF bank is
\[ F_0(z) = H_0(z)H_1(-z) - H_0(-z)H_1(z) \]  
(2)
Let \( P(z) = H_d(z)H(z) \). For PR, \( P(z) \) is required to be a half-band filter.

For the realisation of a low-complexity PR QMF bank, let \( H_d(z) \) be a half-band linear-phase FIR filter of order \( N-1 \), and
\[ H_1(z) = z^{-D} - H_0(z) \]  
(3)
where the variable \( D \) is to be determined. Substituting eqn. 2 into eqn. 1, we obtain
\[
F_0(z) = H_0(z)[(-z)^D-H_0(-z)] - [z^{-D} - H_0(-z)]H_0(z) = z^{-D}[-(1)^D - H_0(z)] - H_0(z) \]
(4)
Thus, to achieve PR, i.e. \( F_0(z) \) is 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 \( H_d(z) \) is sufficiently close to unity as well on the other hand, \( H_d(\omega)^2 \) can be shown to be
\[
|H_1(e^{j\omega})|^2 = 1 - |H_1(e^{j\omega})|^2 - e^{-j\omega} - H_0^2(e^{j\omega}) + |H_0(e^{j\omega})|^2 \]
(5)

In the stopband \( \omega < \pi \), the higher-order term \( |H_d(\omega)|^2 \) is negligible compared with the two terms, if the frequency response of \( |H_d(\omega)|^2 \) is sufficiently attenuated in that band. Accordingly, the fourth-order objective function \( E \) can be reduced to a second-order form as
\[
E = \frac{1}{2\pi} \int_{0}^{\pi} \left[ \int_{0}^{\pi} |H_1(e^{j\omega})|^2 d\omega + \alpha_1 \int_{0}^{\pi} |H_0(e^{j\omega})|^2 d\omega \right] + \alpha_2 \int_{0}^{\pi} |H_0(e^{j\omega})|^2 d\omega \]
(6)

where the \( \alpha \) are the weighting factors, and \( \alpha_2 \) 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.

**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, \( H_s(z) \) can be written as
\[
H_s(z) = H_0(z^2) + 0.5z^{-1}(N-1)/2 \]
(8)
Since \( H_d(z) \) is symmetric, its complexities can be further reduced. The input \( X(z) \) and lower band output \( X_L(z) \) after the analysis filtering are
\[
X(z) = X_0(z^2) + z^{-1}X_1(z) \]
\[ X_L(z) = [H_0(z^2) + 0.5z^{-1}(N-1)/2][X_0(z^2) + z^{-1}X_1(z^2)] \]
(9)
Then, the lower band output after the decimation can be shown to be
\[
X'_L(z) = X_L(z) + 2 = X_0(z^2) + 0.5z^{-1}(N-1)/4X_1(z) \]
(10)
Similarly, the upper band output after the decimation can be shown to be
\[
X'_U(z) = X_U(z) + 2 = z^{-D/2}X_0(z) - X'_L(z) \]
(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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27 May 1998

Electronics Letters Online No: 19981038

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