COMPUTER-AIDED PROGRAM FOR REDUCTION OF TOTAL CAPACITANCE IN CASCADE SC FILTERS

E. Sánchez-Sinencio, J. Ramírez-Angulo and R. L. Geiger

Department of Electrical Engineering
Texas A&M University
College Station, TX 77843

Abstract. - A friendly user-oriented computer program package "AROMA 2" is reported that will design and optimize SC cascade filters to satisfy either magnitude or phase requirements or both. The input data consists of magnitude and/or phase specifications over a frequency range of interest, the program has a built-in design strategy with general default values that permit one to generate an output describing the SC topology and capacitor values, in addition an output file to simulate the overall performance in a SC circuit simulator such as SWITCAP is available. For more experienced designers, AROMA 2 has an interactive mode with several built-in tradeoffs to satisfy more stringent implementation requirements.

I. INTRODUCTION

The design of switched capacitor (SC) filters has been a topic with a lot of attention in recent years. This design has reached certain maturity and there are available several efficient design methods [1] - [2]. It is still a challenging problem to design a switched-capacitor filter within a short period of time having a small capacitance area and satisfying arbitrary design specifications. The problem arises in the fact that biquadratic topology structures, passive sensitivity, and op amp output voltage swings are critical design factors that determine the total capacitance under certain design constraints. In particular, for the case of high order cascade filter designs, another factor that can seriously affect the total capacitance is the pole-zero pairing. It has been shown that an appropriate pole-zero pairing [3] can reduce up to 60% the total capacitance required to implement a SC filter.

In this paper, we address the problem of designing cascade switched-capacitor filters for both amplitude and phase approximations. Futhermore, the following constraints are optimized; passive sensitivity, maximum output voltage swing at each op amp, partial positive feedback, pole-zero pairing. The versatile SC biquad structure chosen has reduced GB effects [4]. This program is a second updated version of AROMA which was previously reported [5].

29th Midwest Symposium on Circuits and Systems
M. Ismail, Editor

AROMA 2 has an easier input format, including the features described before. An optimal pole-zero pairing scheme has been implemented in the new version [3]. Another important new feature of AROMA 2 is the phase approximation capability. The use of SC phase equalizers is common in telecommunication applications in particular with modems. Phase equalizers can correct moderate phase distortion, in the next section we discuss a phase approximation technique which has been implemented in AROMA 2.

II. PHASE APPROXIMATION TECHNIQUE

The phase approximation technique is based on the method proposed by Gregorian and Temes [6] and a pseudo optimization technique [7]. The basic nature of the approximation for an all-pass network design is iterative. The technique here discussed obtains a good initial approximation which is further refined by a computer-aided circuit design algorithm based on a random direction and radial search [7]. This technique provides an arbitrary signal group delay which is often needed in the nonlinear dispersive communication channels. The basic description of the phase approximation follows. Note that the approximation is carried out directly in the z-domain. The transfer function of a sampled-data all-pass system is characterized by:

$$H(z) = \prod_{i=1}^{N/2} \frac{\left(z - e^{j\phi_i}/r_i\right)\left(z - e^{-j\phi_i}/r_i\right)}{\left(z - r_i e^{j\phi_i}\right)\left(z - r_i e^{-j\phi_i}\right)} \qquad (1)$$

where r_i and ϕ_i are the magnitude and phase angle of the ith pole z_i, respectively. For $z = e^{j\omega T}$, the phase of the transfer function (neglecting a linear phase term) can be expressed as:

$$\beta(\omega) = \sum_{i=1}^{N/2} \left\{ \tan^{-1}\left[\frac{\sin\omega T + r_i \sin\phi_i}{\cos\omega T - r_i\cos\phi_i}\right] + \tan^{-1} \right.$$

$$\left.\left[\frac{\sin\omega T - r_i \sin\phi_i}{\cos\omega T - r_i \sin\phi_i}\right]\right.$$

$$-\tan^{-1}\left[\frac{\sin\omega T+\sin\phi_i/r_i}{\cos\omega T-\cos\phi_i/r_i}\right]-\tan^{-1}\left[\frac{\sin\omega T-\sin\phi_i/r_i}{\cos\omega T-\cos\phi_i/r_i}\right]. \quad (2)$$

and the group delay is given by:

$$\tau(\omega)\triangleq -T\frac{d\beta(\omega)}{d\omega}=T\sum_{i=1}^{N/2}\left\{\frac{1-r_i^2}{1+r_i^2-2r_i\cos(\omega T-\phi_i)}\right.$$

$$\left.+\frac{1-r_i^2}{1+r_i^2-2r_i\cos(\omega T+\phi_i)}\right\} \quad (3)$$

The values of ϕ_i are fixed to subdivide the approximating frequency interval in regions spanning the same area under the group delay curve and the values of r_i are calculated according to the following iterative expression [6]:

$$\sum_{j=1}^{i-1}\frac{1-\left(r_j^{(m)}\right)^2}{1+\left(r_j^{(m)}\right)^2-2r_j^{(m)}\cos\left(\phi_i-\phi_j\right)}+\frac{1+r_i^{(m)}}{1-r_i^{(m)}}$$

$$+\sum_{k=i+1}^{N/2}\frac{1-\left(r_k^{(m-1)}\right)^2}{1+\left(r_k^{(m-1)}\right)^2-2r_k^{(m-1)}\cos\left(\phi_i-\phi_j\right)}=\frac{1}{T}\tau_s(\phi_i)$$

$$(4)$$

the iterative process terminates when $max|r_i^{(m)}-r_i^{(m-1)}|\leq \epsilon$, where ϵ is a prescribed error bound. This scheme provides a group delay matching at N/2 frequencies. To obtain the desired group delay in the frequency range of interest within performance bounds a conventional optimization is often used. We propose the use of an efficient pseudo-optimization technique [7] to obtain the desired group delay, this technique has been implemented and results are shown in Section IV.

III. DESIGN ALGORITHM

Step (1): Given the desired frequency specifications either magnitude or phase or both, a magnitude approximation is obtained, the user selects the approximation type: Butterworth, Chebyshev or Elliptic. At this step a normalized low-pass prototype is obtained. If only a phase approximation is desired go directly to step (6).

Step (2): Perform a frequency transformation, according to the desired type of filter, i.e., low-pass, band-pass, high-pass, symmetric notch. The resulting transfer function has the following form:

$$H(s)=\frac{(\alpha_{o_1}+\alpha_{11}s+\alpha_{21}s^2)(\alpha_{o_2}+\alpha_{12}s+\alpha_{22}s^2)...}{(b_{o_1}+b_{11}s+b_{21}s^2)(b_{o_2}+b_{12}s+b_{22}s^2)...}$$

$$\frac{(\alpha_{o_m}+\alpha_{1_m}s+\alpha_{2_m}s^2)}{(b_{o_n}+b_{1_n}s+b_{2_m}s^2)} \quad (5)$$

Step (3): Transform H(s) to obtain H(z) via the bilinear mapping of the form

$$s=k\frac{z-1}{z+1} \quad (6)$$

and

$$k=cot(\omega_c T/2) \quad (7)$$

where ω_c are the critical frequencies in the s-plane i.e., pass-band frequencies, stop-band frequencies. The corresponding H(z) can be expressed as follows:

$$H(z)=\frac{(A_{o_1}+H_{11}z^{-1}+A_{21}z^{-2})...}{(B_{o_1}+B_{11}z^{-1}+B_{21}z^{-2})...}$$

$$\frac{(A_{o_m}+A_{1_m}z^{-1}+A_{2_m}z^{-2})}{(B_{o_n}+B_{i_n}z^{-1}+B_{2_n}z^{-2})} \quad (8)$$

Step (4): Perform a coefficient matching to compute the capacitor component values for each biquadratic function, using a general topological structure [4]. Tradeoffs are involved in the computation of the capacitor values. They include maximum output op amp voltage swing, passive Q-sensitivity, and clock frequency.

Step (5) Determine the optimal pole-zero pairing rendering the minimum total capacitance. Make an exhaustive pole-zero pairing search if the order of the filter is equal or less than 10, otherwise make a limited statistical search [3].

Step (6) Determine the H(z) to satisfy the desired phase response. There exists two possible cases:

i) If a magnitude response in addition to the phase response is needed, then obtain the additional biquadratic functions to both compensate the resulting phase response of the filter satisfying the magnitude response and meet the desired phase response. Compute the corresponding capacitor values (involving the trade-offs) of the biquadratic structure [4].

ii) If only a phase response is specified, then design the biquadratic capacitor values satisfying the desired H(z).

IV. EXAMPLES

In this section, three examples were selected to illustrate the flexibility, functionability and recent improvements of AROMA version 2.

a) *Arbitrary-Delay Low-Pass Filter* - The magnitude response requirements of 0.125 dB ripple and 30 dB attenuation at 1.1 KHz is approximated by AROMA 2 with a 6-th order low-pass elliptic filter. The corresponding group delay response is shown in Fig. 1 by the small broken line, the desired group delay response has an arbitrary shape increasing linearly from about

20 Hz to 500 Hz and decreasing from about 550 Hz to 900 Hz. This was obtained by AROMA 2 and it is shown by the long broken line in Fig. 1. Seven additional biquadratic all-pass filter were required to approximate the arbitrary group delay response. The clock frequency was 32 KHz and the filter total capacitance satisfying the magnitude approximation required 289 $C\mu$ and to satisfy the phase response required 528 C_μ.

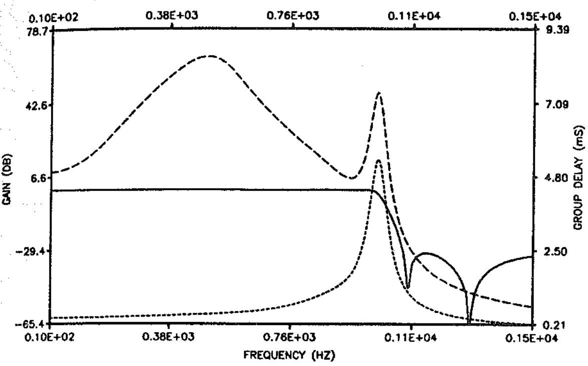

Fig. 1 Low-Pass Elliptic Filter with Arbitrary Group Delay Characteristic.

b) *PCM Filter with Group Delay Equalization* - A popular PCM 5th-order low-pass elliptic filter is designed, in addition a flat group delay in the pass-band of 1.15msec $\pm$ 0.10msec is required. The solid line in Fig. 2 shows the resulting magnitude response. The phase response of the 5th-order filter is shown by the small broken lines. The overall group delay response satisfying the group delay requirements is illustrated with the large broken lines. For a clock frequency of 128 KHz the total capacitance required required was $457C_\mu$, to meet the phase requirements $328C_\mu$ were needed.

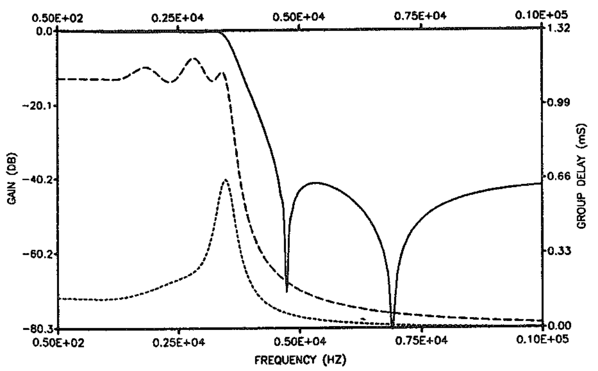

Fig. 2 PCM - Low-Pass Filter with Group Delay Equalization.

c) *Linear-Delay Pulse Compression Filter* A 6th-order elliptic band-pass filter was required to meet the linear-delay pulse compression filter. That is a linear decaying group delay from about 7KHz to 10 KHz. The final result is shown in Fig. 3. The phase response implementation needed about $1,000C_\mu$ for a clock requency of 256 KHz.

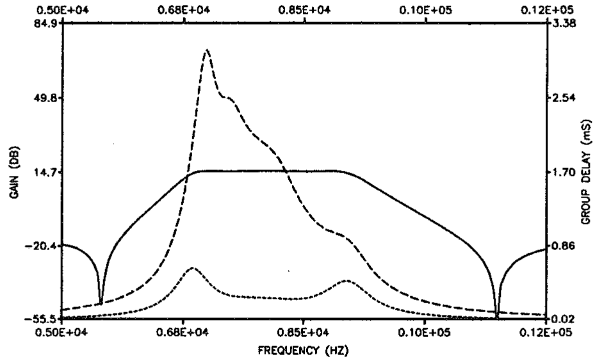

Fig. 3 Linear Delay Pulse-Compression Bandpass Filter.

V. CONCLUSIONS

AROMA 2: An area optimized computer-aided program for cascade SC filter design has been reported. AROMA 2 can handle both phase and magnitude design specifications and renders a cascade biquadratic filter structure with capacitor values satisfying the design specifications. The program contains default values for the novice user, and is interactive allowing the more experienced designer to use AROMA 2 until both frequency performance and cost are optimized.

REFERENCES

[1] R. Gregorian and G. C. Temes, *Analog MOS Integrated Circuits for Signal Processing* New York: John Wiley & Sons, 1986.

[2] P. E. Allen and E. Sánchez-Sinencio, *Switched-Capacitor Circuits.* New York: Van Nostrand Reinhold, 1984.

[3] C. Xuexiang, E. Sánchez-Sinencio and R. L. Geiger, "Pole-Zero Pairing Strategy for Area and Sensitivity Reduction in Cascade SC Filters". *Proc. IEEE/ISCAS*, pp. 609-611, San Jose, May 1986.

[4] E. Sánchez-Sinencio, J. Silva-Martínez, and R. L. Geiger, "Biquadratic SC Filters with Small GB Effects," *IEEE Trans. Circuits & Syst.*, Vol. CAS-31, pp. 876-884, Oct. 1984.

[5] E. Sánchez-Sinencio and J. Ramírez-Angulo, "AROMA: An Area Optimized CAD Program for Cascade SC Filter Design", *IEEE Trans. on Computer-Aided Design*, Vol. CAD-4, pp. 296-303, July 1985.

[6] R. Gregorian and G. C. Temes, "Design Techniques for Digital and Analog All-Pass Circuits", *IEEE Transactions on Circuits and Systems*, Vol. CAS-25, pp. 981-988, Dec. 1978.

[7] J. Ramírez-Angulo, "A Computer-Aided Circuit Design Algorithm Based on a Random Direction and Radial Search," *29th Midwest Symposium on Circuits and Systems*, Lincoln, Nebraska, August 1986.