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Design of the Wave Digital Filters

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1. Introduction

In control automation and robotics filters are used in image processing, in the automatics of alarm system, adaptive signal processing and control vibration, as well as in the control of mobile robots, system identification, speech system recognition, etc.

In this chapter “Design of the Wave Digital filters” we shall propose a very simple procedure for designing, analysis and realization of low-pass, high-pass, band-pass and band-stop wave digital filters from reference LC filters given in the lattice configuration and will be introduced tables for simple design of the wave digital filters.

Wave digital filters are derived from LC-filters. The reference filter consists of parallel and serial connections of several elements. Since the load resistance R is not arbitrary but dependent on the element or source to which the port belongs, we cannot simply interconnect the elements to a network. The elements of the filters are connected with the assistance of serial and parallel adaptors. These adaptors in the discrete form are connected in one port by delay elements. The possibility of changing the port resistance can be achieved using parallel and serial adaptors. These adaptors contain the necessary adders, multipliers and inverters.

2. Serial and parallel adaptors.

In this chapter, we use adaptors with three ports. Blocks the serial and parallel reflection-free adaptors and their signal-flow diagram are shown in figure 1.

The coefficient of the 3-port reflection-free serial adaptor in figure 1A) is calculated from the port resistances R_i $i=1,2$ by (1).

$$B = \frac{R_1}{R_1 + R_2} \quad (1)$$

The coefficient of the reflection-free parallel adaptor in figure 1B) can be calculated from the port conductance G_i $i=1,2$ by (2)

$$A = \frac{G_1}{G_1 + G_2} \quad (2)$$

Fig. 1. A) Three port serial adaptor whose port 3 is reflection-free and its signal flow-graph, B) Three port parallel adaptor whose port 3 is reflection-free and its signal flow-graph.

The coefficients of the dependent parallel adaptor in the figure 2B) can be get from port conductances G_i $i=1,2,3$ by (3)

$$A_1 = \frac{2G_1}{G_1 + G_2 + G_3} \quad A_2 = \frac{2G_2}{G_1 + G_2 + G_3} \quad (3)$$

The coefficients of the dependent serial adaptor in the figure 2A) can be obtained from the port resistances R_i $i=1,2,3$ by (4)

$$B_1 = \frac{2R_1}{R_1 + R_2 + R_3} \quad B_2 = \frac{2R_2}{R_1 + R_2 + R_3} \quad (4)$$

Fig. 2. A) Three-port serial dependent adaptor and its signal-flow graph, B) Three-port parallel dependent adaptor and its signal flow graph.

When connecting adaptors, the network must not contain any feedback loops without a delay element in order to guarantee that the structure is realizable. This means that we cannot connect the dependent adaptors from figure 2A) and 2B). The free-port dependent

parallel is reflection free at port 3 if $G_3 = G_1 + G_2$ and three-port dependent serial adaptor is reflection free if $R_3 = R_1 + R_2$.

3. Examples

By means of examples we shall demonstrate calculation of the low-pass and high-pass wave digital filters. The most important components for the realization of wave digital filters according to Fettweis procedure (Fettweis 1972) are the ladder LC filters. The tables for wave digital structures was designed for the corner frequency $f_1 = 1/(2\pi) = 0.159155$ and sampling frequency $f_s = 0.5$

4. Realization of the low-pas filter.

In the first example we shall realize a Butterworth low-pass of the 5th order and $A_{max} = 3$ dB. In the figure 3 we show the structure of a 5th order ladder LC reference Butterworth filter and its corresponding block connection in the digital form.

Fig. 3. LC reference Butterworth low-pass filter and its corresponding digital block connection.

First we must calculate from figure 3 ($G_0 = 1$) wave port resistances R_1, R_2, R_3, R_4 then the coefficients of the parallel and serial adaptors A_1, B_2, A_3, B_4 and finally the coefficients of the dependent parallel adaptor A_{51}, A_{52} according to (1)-(3).

$$G_1 = G_0 + C_1 = 1.618$$
$$R_1 = \frac{1}{G_1} = 0.618$$
$$R_2 = R_1 + L_2 = 2.236$$
$$G_2 = \frac{1}{R_2} = 0.447$$
$$A_1 = \frac{G_0}{G_0 + C_1} = 0.618$$
$$A_3 = \frac{G_2}{G_2 + C_3} = 0.182$$
$$A_{51} = \frac{2G_4}{G_4 + C_5 + G_5} = 0.467$$

$$G_3 = G_2 + C_3 = 2.447$$
$$R_3 = \frac{1}{G_3} = 0.408$$
$$R_4 = R_3 + L_4 = 2.026$$
$$G_4 = \frac{1}{R_4} = 0.493$$
$$B_2 = \frac{R_1}{R_1 + L_2} = 0.276$$
$$B_4 = \frac{R_3}{R_3 + L_4} = 0.201$$
$$A_{52} = \frac{2G_5}{G_4 + C_5 + G_5} = 0.947$$

The program for the analysis of the wave digital filter of the 5th order written in MATLAB follows, and the frequency response obtained is given in figure 4. The equation in the program for computing XN1-XN4, BN4-BN1,N1-N9 and YN(i) was obtained from the structure in the figure 4.

Fig. 4. Butterworth wave digital low-pass filter of the 5th order.

A1=0.618146;B2=0.276524;A3=0.182858;B4=0.201756;A51=0.467353;A52=0.947276;
N2=0; N4=0; N6=0; N8=0; N10=0; XN=1

```

for i=1:1:200
    XN1=A1*XN-A1*N2+N2;    XN2=XN1+N4;
    XN3=N6-A3*XN2-A3*N6;    XN4=XN3+N8;
    BN4=XN4-A51*XN4+2*N10-A51*N10-A52*N10;
    BN3=XN3-B4*XN4-B4*BN4;
    BN2=XN2-A3*XN2+BN3+N6-A3*N6;
    BN1=XN1-BN2*XN2-B2*BN2;
    N1=XN*A1-A1*N2+BN1;    N3=BN1+BN2;
    N5=BN3-A3*XN2-A3*N6;    N7=BN3+BN4;
    N9=N10-A51*XN4-A51*N10-A52*N10;
    YN(i)=2*N10-A51*XN4-A51*N10-A52*N10;
    N2=N1;N4=N3;N6=N5;N8=N7;N10=N9;XN=0;
end
[h,w]=freqz(YN,1,200)
Plot(w,20*log10(abs(h)))

```

Fig. 5. Frequency response in dB of the Butterworth low-pass filter.

5. Design of the low-pass and high-pass Chebychev filter

As a second example we shall propose low-pass and high-pass Chebychev wave digital filter for $n=5$, $A_{\max}=3$ dB. From table 7 we get the values of the WDF $A_1=0.223$, $B_2=0.226$, $A_3=0.182$, $B_4=0.192$, $A_{51}=0.383$ and $A_{52}=0.360$. Using previous MATLAB program and changing the values of the coefficients we get the attenuation of Chebychev low-pass and high-pass filter in the figure 6. Additionally to get the high-pass filter from the previous program we also have to change $N2=-N1$; $N4=-N3$; $N6=-N5$; $N8=-N7$; $N10=-N9$.

Fig. 6. Attenuation of the Chebychev low-pass and high-pass filter

6. Realization of the low-pass Cauer WDF.

In figure 7 the structure of the 5th order ladder LC reference Cauer low-pass filter is shown. The values of the LC filter was obtained from table (Rudolf Saal, p. 114, 1979) (C 0550 for $\Theta=30^\circ$), $A_{\max}=1.2494$ dB, $A_{\min}=70.5$ dB and $\Omega_s=2.0000$. (Saal 1979).

Fig. 7. LC reference Cauer low-pass filter

Parallel resonant LC circuit in low-pass filter figure 7 wil be realized by digital structure according to Figure 8. Structure of the wave digital Cauer low-pass filter of the 5th order is presented in the Figure 9.

Fig. 8. Discrete realization of parallel and serial LC circuit.

Fig. 9. Structure of the Cauer low-pass filter n=5.

With the assistance of the following MATLAB program we can calculate coefficients of the wave digital filter $A_1, B_2, A_3, B_4, A_{51}$ and A_{52} . The attenuation of the low-pass Cauer filter is presented in Figure 10. The program was obtained from the structure in the Figure 9. The input data of the LC filter was obtained from the catalogue of the Cauer filter (Saal 1979.)

```

C(1)=2.235878; C(3)=2.922148; C(5)=2.092084; L(2)=0.981174; L(4)=0.889139;
C(2)=0.096443; C(4)=0.257662; XN1=1; N2=0; N4=0; N6=0; N8=0; N10=0; N12=0;
N14=0; G(1)=1; G(2)=G(1)+C(1); R2=1/G(2);
R(3)=R(2)+1/(C(2)+1/L(2)); G(3)=1/R(3); G(4)=G(3)+C(3); R(4)=1/G(4);
R(5)=R(4)+1/(C(4)+1/L(4)); G(5)=1/R(5); K(2)=(L(2)*C(2)-1)/(L(2)*C(2)+1);
K(4)=(L(4)*C(4)-1)/(L(4)*C(4)+1); A(1)=G(1)/G(2); B(2)=R(2)/R(3);
A(3)=G(3)/(G(3)+C(3)); B(4)=R(4)/R(5);
A(51)=2*G(5)/(G(5)+C(5)+1); A(52)=2/(G(5)+C(5)+1);
for i=1:1:200

```

```

    XN2=A(1)*XN1+N2-A(1)*N(2); XN3=XN2+N6;
    XN4=N8-A(3)*XN3-A(3)*N8; XN5=XN4+N12;
    BN5=XN5-A(51)*XN5+2*N14-A(51)*N14-A(52)*N14;
    BN4=XN4-B(4)*BN5-B(4)*XN5;
    BN3=XN3-A(3)*XN3+BN4+N8-A(3)*N8;
    BN2=XN2-B(2)*XN3-B(2)*BN3;
    N1=A(1)*XN1-A(1)*N2+BN2; N3=BN2*BN3;
    N5=-K(2)*N3+K(2)*N6+N4; N7=BN4-A(3)*XN3-A(3)*N8;
    N9=BN4+BN5; N11=N10-N9*K(4)+N12*K(4);

```



```
N13=N14-A(51)*XN5-A(51)*N14-A(52)*N14;  
YN(i)=2*N14-A(51)*XN5-A(52)*N14-A(51)*N14;  
N2=N1;N4=N3;N6=N5;N8=N7;N10=N9;N12=N11;N14=N13;XN1=0;  
end  
[h,w]=freqz(YN,1,200); plot(w,20*log10(abs(h)))
```

High-pass can be obtained by changing in the program $N2=-N1$; $N4=-N3$; $N6=-N5$; $N8=-N7$; $N10=-N9$; $N12=-N11$; $N14=-N13$. In Figure 10 the attenuation of low-pass and high-pass filter are presented.

Fig. 10. Frequency response of the Cauer low-pass and high-pass wave digital filter

7. Design of the Cauer band-pass filter

We shall realize band-pass filter that accomplish the tolerance scheme given in Figure 11. The values of the normalized low-pass filter for C0350 $\theta=53$ can be obtained from the table of Cauer filter (Saal 1979). The values of the normalized low-pass filter are shown in figure 12A. With the transformation of the low-pass filter to the band-pass filter can be obtained values of the band-pass filter presented in Figure 12B.

Fig. 11.Tolerance scheme of the band-pass filter.

Fig. 12. A) LC low-pass Cauer filter, B) LC band-pass Cauer filter, C) LC band-pass filter after impedance transformation.

Serial-parallel resonant circuit in the longitudinal branch in the figure 12B) can be transformed into parallel-parallel resonant circuit, figure 13, by equations (5) up to (11).

Fig. 13. Impedance transformation of the serial-parallel resonant LC circuit to the parallel-parallel resonant circuit

$$a = \left(1 + \frac{C_{A1}}{C_{A2}} + \frac{L_{A2}}{L_{A1}} \right)^2 - 4 \frac{C_{A1}L_{A2}}{C_{A2}L_{A1}} \quad (5)$$

$$u = \sqrt{1 - \frac{4L_{A2}}{aL_{A1}}} \quad (6)$$

$$v = \sqrt{1 - \frac{4C_{A1}}{aC_{A2}}} \quad (7)$$

$$L_{B2} = L_{A1} \frac{1+u}{2} \quad (8)$$

$$L_{B1} = L_{A1} \frac{1-u}{2} \quad (9)$$

$$C_{B2} = aC_{A2} \frac{1 + v}{2} \tag{10}$$

$$C_{B1} = aC_{A2} \frac{1 - v}{2} \tag{11}$$

From the circuit in the figure 14 can be obtained the values $Y_i=C_i+1/L_i$ ($i=1, 2, 3, 4$) of the parallel resonant circuit and the resistance R_1, R_2, R_3 and R_4 at the output port of each adaptors. Parallel resonant circuit can be realized by the discrete structure presented in figure 8. The coefficients K_i $i=(1, 2, 3, 4)$ of the wave digital band-pass filter presented in figure 8 can be obtained by following equation

$$K_i = \frac{L_iC_i - 1}{L_iC_i + 1}$$

$K_1=0.543105$

$K_2=-0.11659$

$K_3=0.870278$

$K_4=0.543105$

Fig. 14. Cauer LC band-pass filter after the impedance transformation

From the port admittances Y_i and impedances R_i we get the following values,

$G_1=G_0+Y_1=4.39611$

$R_1=0.227432$

$R_2=R_1+1/Y_2=0.463853$

$R_3=R_2+1/Y_3=0.581104$

$G_3=1.720862$

and the coefficients of the parallel and serial adaptors of the wave digital band-pass in the figure 15. At the output of the band-pass filter the parallel dependent adaptor must be used in order to realize the load resistor $R_4=1$.

$A_1 = \frac{G_0}{G_0 + G_1} = \frac{1}{1 + 3.3969} = 0.2274$

$B_2 = \frac{R_1}{R_1 + Z_2} = \frac{0.2274}{0.2274 + 0.2364} = 0.4903$

$B_3 = \frac{R_2}{R_2 + Z_3} = \frac{0.4638}{0.4638 + 0.1172} = 0.7982$

$A_{41} = \frac{2G_3}{G_3 + Y_4 + G_4} = \frac{2 \cdot 1.7208}{1.7208 + 3.3969 + 1} = 0.5625$

$A_{42} = \frac{2 \cdot G_4}{G_3 + Y_4 + G_4} = \frac{2}{1.7208 + 3.3969 + 1} = 0.3269$

Fig. 15. Cauer wave digital band-pass filter.

8. Tables of the Wave digital filters.

In the figure 16 there are frequency response and structure of the wave digital filter. The structure of Butterworth WDF is created by connection of the parallel and serial adaptors terminated at the port 3 with delay elements. At the end of the structure must be connected parallel dependent adaptor to realize for n odd load resistance $R_L=1$. In case of n even at the end of structure must be connected serial dependent adaptor.

9. Tables of the Butterworth wave digital filter

Fig. 16. Frequency response and structure of the Butterworth wave digital filter.

In tables 1-5 are the elements of the Butterworth wave digital filters for various attenuation $A_{\max}$ in the pass-band and $n=3, 4, 5, 6$ and 7 . The tables was designed for sampling frequency $f_s=0.5$.

$A_{\max}$	A_1	B_2	A_{31}	A_{32}
0.1	0.6517	0.3788	0.5494	0.9453
0.2	0.6246	0.3419	0.5096	0.9309
0.3	0.6082	0.3206	0.4856	0.9210
0.4	0.5962	0.3056	0.4682	0.9133
0.5	0.5867	0.2941	0.4545	0.9068
0.6	0.5789	0.2846	0.4331	0.9012
0.7	0.5721	0.2767	0.4334	0.8963
0.8	0.5662	0.2698	0.4249	0.8918
0.9	0.5609	0.2637	0.4174	0.8876
1.0	0.5561	0.2583	0.4105	0.8838

Table 1. Elements of the Butterworth WDF $N=3$, $A_{\max}$ in dB.

$A_{\max}$	A_1	B_2	A_3	B_{41}	B_{42}
0.1	0.6764	0.3694	0.3210	0.5690	0.9679
0.2	0.6568	0.3424	0.2924	0.5385	0.9599
0.3	0.6449	0.3268	0.2760	0.5200	0.9545
0.4	0.6364	0.3157	0.2645	0.5067	0.9503
0.5	0.6295	0.3071	0.2556	0.4961	0.9468
0.6	0.6239	0.3000	0.2484	0.4874	0.9437
0.7	0.6190	0.2941	0.2423	0.4798	0.9409
0.8	0.6147	0.2889	0.2369	0.4732	0.9385
0.9	0.6109	0.2843	0.2326	0.4673	0.9362
1.0	0.6074	0.2802	0.2281	0.4620	0.9431

Table 2. Elements of the Butterworth WDF $N=4$, $A_{\max}$ in dB.

$A_{\max}$	A_1	B_2	A_3	B_4	A_{51}	A_{52}
0.1	0.7022	0.3784	0.2876	0.3188	0.6021	0.9815
0.2	0.6872	0.3658	0.2655	0.2951	0.5781	0.9722
0.3	0.6782	0.3531	0.2532	0.2813	0.5636	0.9742
0.4	0.6716	0.3441	0.2446	0.2717	0.5530	0.9718
0.5	0.6664	0.3371	0.2380	0.2642	0.5446	0.9699
0.6	0.6621	0.3313	0.2325	0.2580	0.5376	0.9682
0.7	0.6584	0.3264	0.2280	0.2529	0.5317	0.9667
0.8	0.6551	0.3222	0.2240	0.2484	0.5264	0.9653
0.9	0.6522	0.3184	0.2205	0.2444	0.5217	0.9641
1.0	0.6495	0.3149	0.2173	0.2408	0.5174	0.9629

Table 3. Elements of the Butterworth WDF $N=5$, $A_{\max}$ in dB.

$A_{\max}$	A_1	B_2	A_3	B_4	A_5	B_{61}	B_{62}
0.1	0.7256	0.4125	0.2871	0.2635	0.3355	0.6363	0.9895
0.2	0.7131	0.3944	0.2696	0.2458	0.3149	0.6170	0.9870
0.3	0.7066	0.3837	0.2595	0.2356	0.3029	0.6053	0.9854
0.4	0.7014	0.3761	0.2523	0.2284	0.2948	0.5968	0.9841

0.5	0.6072	0.3702	0.2468	0.2229	0.2879	0.5901	0.9830
0.6	0.6938	0.3653	0.2422	0.2184	0.2824	0.5845	0.9821
0.7	0.6909	0.3611	0.2384	0.2145	0.2779	0.5797	0.9831
0.8	0.6883	0.3574	0.2350	0.2112	0.2739	0.5754	0.9805
0.9	0.6859	0.3542	0.2321	0.2083	0.2703	0.5716	0.9798
1.0	0.6838	0.3512	0.2294	0.2056	0.2671	0.5681	0.9792

Table 4. Elements of the Butterworth WDF N=6, $A_{\max}$ in dB.

$A_{\max}$	A_1	B_2	A_3	B_4	A_5	B_6	A_{71}	A_{72}
0.1	0.7462	0.4392	0.2994	0.2497	0.2628	0.3597	0.6679	0.9940
0.2	0.7635	0.4236	0.2842	0.2352	0.2473	0.3415	0.6522	0.9927
0.3	0.7307	0.4144	0.2754	0.2268	0.2384	0.3308	0.6428	0.9917
0.4	0.7265	0.4078	0.2692	0.2208	0.2320	0.3232	0.6358	0.9911
0.5	0.7231	0.4027	0.2643	0.2162	0.2271	0.3173	0.6304	0.9904
0.6	0.7204	0.3984	0.2603	0.2125	0.2231	0.3125	0.6258	0.9899
0.7	0.7280	0.3948	0.2569	0.2093	0.2197	0.3083	0.6218	0.9895
0.8	0.7159	0.3916	0.2539	0.2065	0.2168	9.3047	0.6184	0.9890
0.9	0.7140	0.3887	0.2513	0.2041	0.2142	0.3015	0.6153	0.9887
1.0	0.7123	0.3862	0.2490	0.2019	0.2118	0.2986	0.6124	0.9883

Table 5. Elements of the Butterworth WDF N=7, $A_{\max}$ in dB.

10. Tables of the Chebychev wave digital filter

In tables 6-9 are the elements of Chebychev wave digital filters for various attenuation $A_{\max}$ in the pass-band and $n=3, 5, 7$ and 9 . The tables was designed for sampling frequency $f_s=0.5$.

Fig. 17. Frequency response and structure of Chebychev wave digital filter

$A_{\max}$	A_1	B_2	A_{31}	A_{32}
0.10	0.4922	0.3022	0.4620	0.7574
0.25	0.4341	0.2774	0.4310	0.6812
0.50	0.3852	0.2599	0.4126	0.6114
1.00	0.3307	0.2496	0.3995	0.5293
2.00	0.2695	0.2445	0.3929	0.4331
3.00	0.2300	0.2442	0.3925	0.3696

Table 6. Elements of Chebychev WDF N=3, $A_{\max}$ in dB.

A_{max}	A_1	B_2	A_3	B_4	A_{51}	A_{52}
0.10	0.4658	0.2536	0.2161	0.2245	0.4179	0.7374
0.25	0.4197	0.2404	0.2059	0.2132	0.3987	0.6721
0.50	0.3696	0.2311	0.1975	0.2044	0.3869	0.5965
1.00	0.3190	0.2262	0.1911	0.1981	0.3798	0.5168
2.00	0.2610	0.2251	0.1857	0.1933	0.3797	0.4229
3.00	0.2231	0.2265	0.1828	0.1922	0.3830	0.3608

Table 7. Elements of Chebychev WDF N=5, A_{max} in dB.

A_{max}	A_1	B_2	A_3	B_4	A_5	B_6	A_{71}	A_{72}
0.10	0.4585	0.2437	0.2022	0.1947	0.1962	0.2123	0.4049	0.7313
0.25	0.4087	0.2316	0.1944	0.1884	0.1903	0.2028	0.3875	0.6550
0.50	0.3653	0.2250	0.1893	0.1861	0.1867	0.1968	0.3872	0.5925
1.00	0.3158	0.2213	0.1847	0.1834	0.1836	0.1919	0.3735	0.4206
2.00	0.2587	0.2210	0.1805	0.1814	0.1812	0.1880	0.3734	0.3921
3.00	0.2213	0.2227	0.1783	0.1806	0.1802	0.1862	0.3782	0.3589

Table 8.Elements of Chebychev WDF N=7, A_{max} in dB

A_{max}	A_1	B_2	A_3	B_4	A_5	B_6	A_7	B_8	A_{91}	A_{92}
0.10	0.4554	0.2399	0.1970	0.1886	0.1854	0.1860	0.1908	0.2081	0.4000	0.7287
0.25	0.4064	0.2287	0.1912	0.1847	0.1821	0.1825	0.1863	0.1996	0.3836	0.6569
0.50	0.3636	0.2227	0.1867	0.1823	0.1800	0.1844	0.1834	0.1943	0.3751	0.5908
1.00	0.3145	0.2193	0.1826	0.1804	0.1783	9.1787	0.1811	0.1899	0.3708	0.5123
2.00	0.2578	0.2194	0.1789	0.1790	0.1769	0.1773	0.1793	0.1864	0.3273	0.4196
3.00	0.2205	0.2213	0.1769	0.1784	0.1763	0.1604	0.1647	0.1873	0.3753	0.3583

Table 9.Elements of Chebychev WDF N=9, A_{max} in dB

11. Tables of Cauer wave digital filter

In tables 10-12 are the elements of Cauer wave digital filters for various attenuation A_{max} in the pass-band and N=3, 5 and 7. The tables was designed for sampling frequency $f_s=0.5$.

Fig. 18. Frequency response and structure of Cauer filter

C	A _s	A ₁	B ₂	A ₃₁	A ₃₂
0.0004	24.7	0.7504	0.5766	0.7314	0.9629
0.0017	30.7	0.7209	0.4907	0.6664	0.9374
0.0039	34.3	0.6673	0.4569	0.6272	0.9160
0.0109	38.7	0.6190	0.4063	0.5778	0.8803
0.0279	42.8	0.5706	0.3612	0.5339	0.8365
0.0436	44.8	0.5461	0.3459	0.5140	0.8114
0.0988	48.3	0.4983	0.3161	0.4804	0.7573
0.1773	50.9	0.4614	0.2979	0.4590	0.7110
0.2803	53.0	0.4306	0.2855	0.4442	0.6699
1.2494	60.0	0.3147	0.2593	0.4118	0.4999

Table 10. Elements of Cauer WDF N=3, Ω_s=4.8097, K₂=-0.93686

A _{max}	A _s	A ₁	B ₂	A ₃	B ₄	A ₅₁	A ₅₂
0.0017	41.3	0.657	0.399	0.330	0.436	0.734	0.915
0.0039	44.8	0.627	0.373	0.311	0.404	0.690	0.893
0.0109	49.2	0.585	0.343	0.290	0.369	0.639	0.856
0.0279	53.3	0.543	0.318	0.272	0.341	0.596	0.813
0.0436	55.3	0.522	0.306	0.264	0.323	0.577	0.788
0.0988	58.8	0.479	0.288	0.251	0.310	0.546	0.736
0.1773	61.4	0.446	0.277	0.243	0.298	0.527	0.691
0.2803	63.5	0.418	0.270	0.237	0.289	0.514	0.652
1.2494	70.5	0.309	0.256	0.221	0.269	0.492	0.487

Table 11. Elements of Cauer WDF N=5, Ω_s=2.000, K₂=-0.827, K₄=-0.627

A _{max}	A _s	A ₁	B ₂	A ₃	B ₄	A ₅	B ₆	A ₇₁	A ₇₂
0.0004	43.5	0.6901	0.4211	0.3521	0.4838	0.4446	0.4972	0.8781	0.9364
0.0017	49.5	0.6543	0.3827	0.3240	0.4464	0.4166	0.4471	0.7973	0.9071
0.0039	53.0	0.6167	0.3611	0.3093	0.4274	0.4015	0.4209	0.7502	0.8844
0.0109	57.5	0.5776	0.3353	0.2924	0.4064	0.3841	0.3912	0.6972	0.8482

0.0279	61.6	0.5375	0.3134	0.2785	0.3897	0.3698	0.3672	0.6527	0.8056
0.0436	63.5	0.5168	0.3038	0.2725	0.3826	0.3636	0.3569	0.6293	0.7766
0.0988	67.1	0.4758	0.2880	0.2624	0.3712	0.3534	0.3401	0.6015	0.7300
0.1773	69.7	0.4434	0.2784	0.2558	0.3642	0.3470	0.3295	0.5823	0.6862
0.2803	71.7	0.4158	0.2720	0.2511	0.3593	0.3425	0.3221	0.5697	0.6472
1.2494	78.7	0.3084	0.2606	0.2378	0.3475	0.3310	0.3035	0.5484	0.4845

Table 12. Elements of Causer WDF N=7, $\Omega_s=1.41421$, $K_2=-0.7815$, $K_4=-0.3491$, $K_6=-0.4867$

12. Realization of wave digital filters with DSP C6711 by SIMULINK

The simulink models of the parallel and serial adaptors figure 19 was added in the simulink browse library between common used block.

Fig. 19. Models of the serial and parallel adaptors deposited in simulink browse library.

Fig. 20. Parallel and serial adaptors deposited in simulink browse library.

The simulink model of the fifth order filter in the figure 4 corresponds to the realization of a wave digital filter application on TMS320C6711 DSK using Embedded Target for Texas Instruments TMS320C6000 DSP Platform. The model of the filter, figure 21, was created by means of serial and parallel block that were added to the window simulink library browser. In the output and input of WDF were added ADC and DAC convertors of the TMS320C6711 that are in the simulink library browser, Embedded Target for TI C6000 DSP and C6711DSK board support.

Fig. 21. Realization of fifth order wave digital filter by TMS320C6711 simulink.

This project created in code composer studio can be seen in figure 22 and can run on the DSPC6711.

Fig. 22. Projects of the realization of Wave digital filter by TMS320C6711

13. Bank of filters with Chebychev and inverse Chebychev wave digital filters

In this example we shall design bank of filters with wave digital filters. We use Chebychev filter for order $N=3$ and $A_{\max}=0.1$ dB. Transfer function of the Chebychev low-pass we obtain by matlab using the commands $[a,b]=\text{cheby1}(3,0.1,0.5,'s')$

$$H_0(s)=\frac{1}{2.0353s^3+2.0116s^2+2.5206s+1.0000}=\frac{1}{h_0(s)}$$
$$F(s)=\frac{1}{2.0353s^3+1.5265s}=\frac{1}{f(s)}$$

From these equations we can obtain input impedance $Z_e(s)$ of the circuit and the structure in figure 23.

$$Z_e(s)=\frac{h_0(s)+f(s)}{h_0(s)-f(s)}=\frac{4.0707s^3+2.0116s^2+4.0472s+1}{2.0116s^3+0.9941s^2+1}$$
$$Z_e(s)=\frac{1}{2.0235s+\frac{1}{0.9941s+\frac{1}{2.0235s+1}}}$$

Fig. 23. LC prototype of Chebychef low-pass filter.

From the LC prototype of the Chebychev filter we obtain discrete realization of the wave digital filter that is demonstrate in figure 24, where

$A_1=0.3307$ $B_2=0.2496$ $A_{31}=0.3995$ $A_{32}=0.5293$

Fig. 24. Low-pass wave digital filter with the values of the elements $A_1=0.3307$, $B_2=0.2496$, $A_{31}=0.3995$, $A_{32}=0.5293$.

In the parte synthesis of the bank of filters we choose low-pass Chebychev inverse filter that is inverse to the low-pass in the part of analysis bank.

Fig. 25. LC Chebychev inverse filter

From the Chebychev inverse filter figure 25, the coefficients of the parallel and serial adaptor are

$A_1=0.6693$ $B_2=0.2496$ $A_{31}=0.7032$ $A_{32}=0.5293$ $K=0.1428$

Fig. 26. Low-pass wave digital filter Chebychev inverse with coefficients $A_1=0.6693$, $B_2=0.2496$, $A_{31}=0.7032$, $A_{32}=0.5293$, $K=0.1428$.

Normalized attenuation of the low-pass and high-pass filter is demonstrated in the figure 27.

Fig. 27. Normalized attenuation of the filter bank.

In the figure 28 is presented analysis part of the filter bank. This part is designed by Chebychev low-pass filter and inverse Chebychev high-pass filter. The coefficients of the chebychev low-pass filter are $A1=0.3307$, $B2=0.2496$, $A31=0.3995$ and $A32=0.5293$. The coefficients of inverse Chebychev high pass filter are $A1=0.6692$, $B2=0.2496$, $A31=0.7032$, $A32=0.5293$ and $K=0.1428$. In the adders connected in the output of the delay elements must be changed the signature because must be fulfill the condition $H_1(z)=G_0(-z)$, where $G_0(z)$ is the transfer function of the inverse Chebychev low-pass transfer function from the Synthesis filter bank from figure 29.

Fig. 28. Analysis wave digital filter bank

In the figure 29 is presented synthesis part of the filter bank. This part is designed by Chebychev inverse low-pass filter and Chebychev high-pass filter. The coefficients of the chebychev low-pass filter are $A1=0.3307$, $B2=0.2496$, $A31=0.3995$ and $A32=0.5293$. The coefficients of inverse Chebychev high pass filter are $A1=0.6692$, $B2=0.2496$, $A31=0.7032$,

$A_{32}=0.5293$ and $K=0.1428$. In the adders, connected in the output of the delay elements of the Chebychev high-pass wave digital filter, must be changed the signature because must be fulfill the condition $G_1(z)= -H_0(-z)$, where $H_0(z)$ is the transfer function of the Chebychev low-pass transfer function from the Analysis filter bank, figure 28.

Fig. 29. Synthesis wave digital filter bank

In figure 30 is presented the model of the filter bank composed from analysis and synthesis parts and from down-sampler and sub-sampler. The input is connected to a speech signal saved in Workspace1. The output of the filter-bank was connected with oscilloscope. Figure 31 shows speech signal in the input and the output of the filter bank and spectrograms of a speech signal in the output and input of the filter bank. From the responses in the figure 31 we can deduce that filter bank composed from Chebychev and Inverse Chebychev filter has the good properties.

Fig. 30. Simulink model of the wave digital filter bank

Fig. 31. Diagrams of the voice in the input and output of the wave digital filter bank.

14. Conclusion

Though the structure of the wave digital filter is more complicated than other structures, the algorithm for implementation on the DSP is very simple and it is very easy to propose the general algorithm for the arbitrary order of the wave digital filter. These structures are not too much sensitive to the error of quantization as other types of the filters. With small modification of the presented programs can be created another tables of the WDF. The parts of the programs can be utilized for implementing of the wave digital filters in digital signal processors DSP. In this chapter was constructed filter-bank from Chebychev and Inverse Chebychev filter. This filter bank was simulated by Signal Processing toolbox of MATLAB contains the speech signal saved in Worspace1. In the figure 31 we have illustrated results obtained by analysis of a speech signal using the Signal Processing Toolbox in MATLAB.

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The present edited book is a collection of 18 chapters written by internationally recognized experts and well-known professionals of the field. Chapters contribute to diverse facets of automation and control. The volume is organized in four parts according to the main subjects, regarding the recent advances in this field of engineering. The first thematic part of the book is devoted to automation. This includes solving of assembly line balancing problem and design of software architecture for cognitive assembling in production systems. The second part of the book concerns different aspects of modelling and control. This includes a study on modelling pollutant emission of diesel engine, development of a PLC program obtained from DEVS model, control networks for digital home, automatic control of temperature and flow in heat exchanger, and non-linear analysis and design of phase locked loops. The third part addresses issues of parameter estimation and filter design, including methods for parameters estimation, control and design of the wave digital filters. The fourth part presents new results in the intelligent control. This includes building a neural PDF strategy for hydroelectric saturation simulator, intelligent network system for process control, neural generalized predictive control for industrial processes, intelligent system for forecasting, diagnosis and decision making based on neural networks and self-organizing maps, development of a smart semantic middleware for the Internet, development of appropriate AI methods in fault-tolerant control, building expert system in rotary railcar dumpers, expert system for plant asset management, and building of a image retrieval system in heterogeneous database. The content of this thematic book admirably reflects the complementary aspects of theory and practice which have taken place in the last years. Certainly, the content of this book will serve as a valuable overview of theoretical and practical methods in control and automation to those who deal with engineering and research in this field of activities.

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