Multimedia-Based Analog and Digital Filter Design

DAVID BÁEZ-LÓPEZ,[1,2] GUSTAVO CABRERA,[1] PABLO MARTÍNEZ,[1] GERARDO REYES,[1]
R. JAROSZYNSKI,[1] J. LUNA,[1] J. M. RAMÍREZ,[1] G. ESPINOSA FLORES-VERDAD[2]

[1] *Departamento de Ingeniería Electrónica, Universidad de las Américas–Puebla, Cholula, Puebla, Mexico*

[2] *Departamento de Electrónica, Instituto Nacional de Astrofisica, Optica y Electrónica, A.P. 51, Tonantzintla, Puebla 72000, Mexico*

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ABSTRACT: In this article a multimedia software package used to design analog and digital filters is described. This package runs on an IBM-compatible PC under Windows and is called WinFiltros. With WinFiltros, students or practicing engineers should be able to complete an analog or digital filter design in a few seconds, giving more attention to what it can be done with a filter instead of getting endless cumbersome numerical calculations. Several examples showing how WinFiltros works are included. © 1998 John Wiley & Sons, Inc. Comput Appl Eng Educ 6: 1–8, 1998

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INTRODUCTION

Electric filters have a relevant importance in electronic systems because they are present in almost any system. For example, communication systems make intensive use of filtering to separate unwanted noise from the desired signal. Power supplies use filters to reject ripple and improve the dc signal quality. Audio equalizers use filters to amplify or attenuate bands in the audio range to improve audio quality depending upon room acoustic characteristics. Digital video needs digital filters to reduce noise due to coding and transmission through a noisy channel.

Filter design is an intensive computational task requiring a significant amount of numerical calculations to obtain either the parameters of a filter transfer function or the element values for filter circuit realization.

On the other hand, computer usage has reached every corner in everyday life. Thus, computer software development has become an important part of technological development. An area that has been most influenced by this development is education. Everyday, new software becomes available to enhance the teaching procedure [1–3]. Nowadays, there exists a large number of software packages especially dedicated to filter design, but they have several drawbacks. Two of the most important drawbacks are (a) these packages have a very high price, sometimes running into several thousands of dollars, and (b) usually they are useful to design only either analog or digital filters.

This article describes a software package which has a multimedia approach. Its purpose is to provide a tool to be used as a teaching aid in analog and digital filter design courses [4–6].

Correspondence to D. Báez-López (dbaez@circuitos.inaoep.mx).

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Table 1 Options Available for Analog and Digital Filters

	Analog	Digital	
		Recursive	Nonrecursive
Approximation	Butterworth Chebyshev Inverse-Chebyshev Elliptic Thomson	Butterworth Chebyshev Inverse-Chebyshev Elliptic Thomson	Parks method Window method
Realization	Cascade of second-order biquads Sallen and Key Multiple feedback KHN Tow-Thomas GIC Twin-T Passive ladder realization Butterworth Chebyshev Thomson	Cascade of second-order stages	*n*th-order circuit

There are several advantages in having a tool similar to the one described in this article. First, it takes care of all the cumbersome calculations which do not provide insight into the solution of the problem. Second, it allows students to design a complete filter from specifications at the click of a mouse. Finally, it allows one to design any kind of filter, either analog or digital, passive or active, and it has several options to design an active RC analog filter from several available topologies. Several videos are inserted in the package to allow for visual and oral explanations of what the user can obtain with such designs.

MULTIMEDIA WINFILTROS

As described above, the package named Multimedia WinFiltros (in short, WinFiltros) can be used to design analog and one-dimensional digital filters with several options for each type of filter designed. These options are summarized in Table 1.

As can be seen in Table 1, WinFiltros is capable of handling the two fundamental problems of filter design: approximation and synthesis. The available approximations that can be used for magnitude approximation include Butterworth, Chebyshev, inverse-Chebyshev, Cauer or elliptic, and Thomson. For synthesis of the network, WinFiltros has the capability of obtaining either the passive ladder circuit (not available for elliptic or inverse-Chebyshev) or a cascade of second-order stages (for an odd order there is a first-order stage) where the user has the freedom to choose from a number of different configurations such as Sallen-Key, multiple feedback (including the Friend biquad), state variable KHN, Tow-Thomas, GIC-based stage, and twin-T configurations [4,6].

WinFiltros includes a set of animations, videos, and oral explanations of what can be achieved with each of the topics by giving brief theoretical background on each of the approximation and synthesis topics, showing different advantages, disadvantages, and limitations of the active-RC biquad chosen. For example, for the Sallen and Key active filter it describes its Q limitation that can be realized (a maximum $Q = 5$) and its high sensitivity, while for the KHN it mentions its low-sensitivity property [4].

Each screen in WinFiltros has buttons to request actions to be taken by WinFiltros. For example, the input window (see Fig. 2) has two sets of buttons. The uppermost one allows students to open and save files, evaluate transfer function parameters, and get help. The following set of buttons allows the user to watch videos and listen to explanations about each topic. There is also a set of four windows used to enter data for the filter to be designed. Here, we select the bandpass and stopband frequencies as well as the attenuations in these bands. Also, the

Figure 1 Main menu window.

user selects the units to be used for frequency. In addition, the user selects if the filter to be designed is either analog or digital.

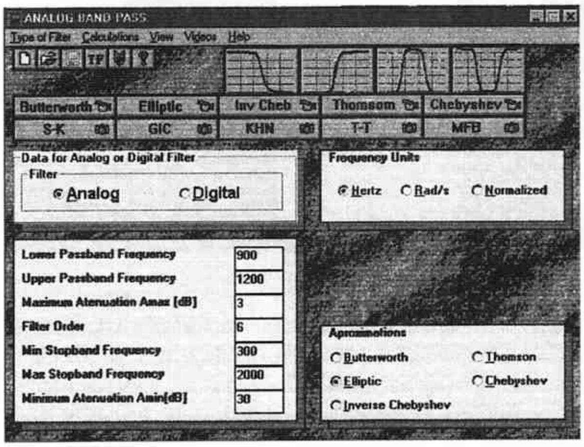
THEORETICAL BACKGROUND

Approximation Techniques

The approximation techniques used in WinFiltros are the ones available almost in any filter design course [4]: namely, Butterworth, Chebyshev, inverse-Chebyshev, Cauer or elliptic, and Thomson. These approximation characteristics were chosen because they are the ones most used in textbooks dedicated to filter design [4–6].

Spectral Transformation

Calculations are first done for lowpass filters. Spectral transformations are used to obtain desired parameters for highpass, bandpass, and band-reject filters. A frequency denormalization is usually needed to scale for the desired cutoff frequencies [4].



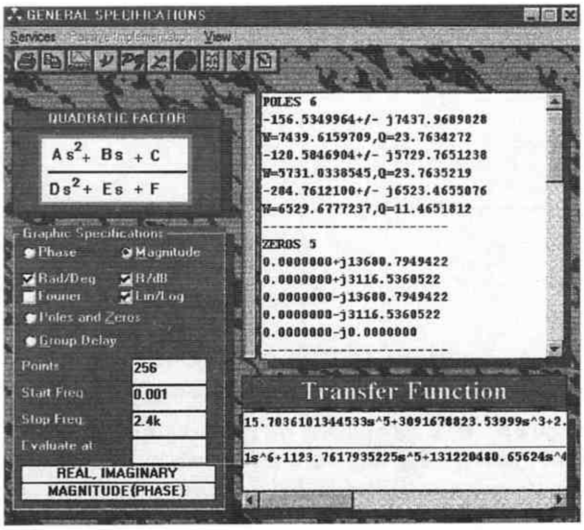
Data for Analog or Digital Filter
Filter
● Analog ○ Digital

Frequency Units
● Hertz ○ Rad/s ○ Normalized

Lower Passband Frequency 900
Upper Passband Frequency 1200
Maximum Atenuation Amax [dB] 3
Filter Order 6
Min Stopband Frequency 300
Max Stopband Frequency 2000
Minimum Atenuation Amin[dB] 30

Aproximations
○ Butterworth ○ Thomson
● Elliptic ○ Chebyshev
○ Inverse Chebyshev

Figure 2 Input window. Data are entered for an elliptical bandpass filter.



$$\frac{As^2 + Bs + C}{Ds^2 + Es + F}$$

```
POLES 6
-156.5349964+/- j7437.9689828
W=7439.6159709,Q=23.7634272
-120.5846904+/- j5729.7651238
W=5731.0338545,Q=23.7635219
-284.7612100+/- j6523.4655076
W=6529.6777237,Q=11.4651812
------------------------
ZEROS 5
0.0000000+j13680.7949422
0.0000000+j3116.5360522
0.0000000-j13680.7949422
0.0000000-j3116.5360522
0.0000000-j0.0000000
------------------------
```

Graphic Specifications
● Phase ○ Magnitude
☑ Rad/Deg ☑ R/dB
☐ Fourier ☑ Lin/Log
● Poles and Zeros
● Group Delay

Points 256
Start Freq 0.001
Stop Freq 2.4k
Evaluate at

```
15.7036101344533s^5+3091678823.53999s^3+2.
1s^6+1123.7617935225s^5+131220480.65624s^4
```

Figure 3 Output window. Poles and zeros are displayed in the top right window. Quadratic factors can be seen by scrolling down. The complete transfer function can be seen by scrolling the bottom right window. Buttons in the top left corner allow users to execute different actions.

Digital Filters

The package is able to obtain analog and digital IIR and FIR filters. For digital IIR filters, the transfer

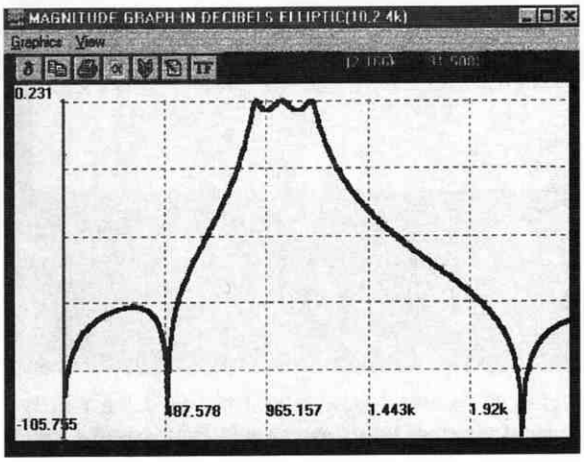


Figure 4 Magnitude plot for the elliptical bandpass filter. The mouse position indicates the value of the magnitude at that frequency point.

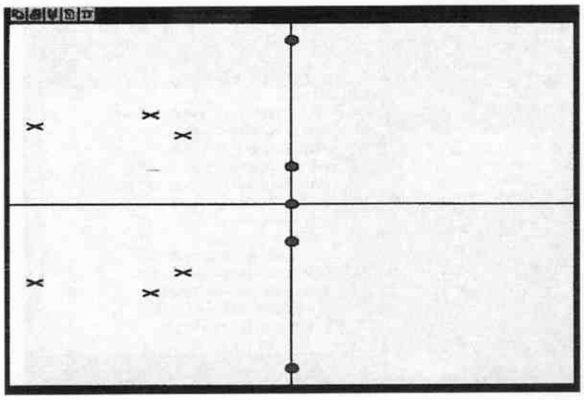
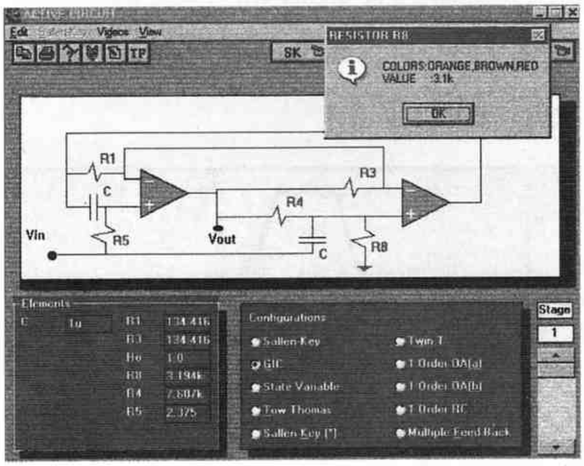


Figure 5 Pole-zero plot for the elliptical bandpass filter. Users can see that the magnitude bandstop behavior is due to the zeros located on the imaginary $j\omega$ axis. Also, positioning the mouse on top of a zero or pole gives its coordinates.

function is obtained directly by transformation from the analog transfer function. To this purpose, the user can choose the transformation from any one of the following ones: bilinear, forward, or backward. For FIR digital filters, they can be designed using either the windows or Parks techniques [6].

Passive Filters

Passive filter design is available for Butterworth, Chebyshev, and Thomson filters. The topology used is the ladder low-sensitivity one. The terminating resistances are chosen by the user. The limitations



RESISTOR R8

COLORS:ORANGE,BROWN,RED
VALUE :3.1k

OK

Elements

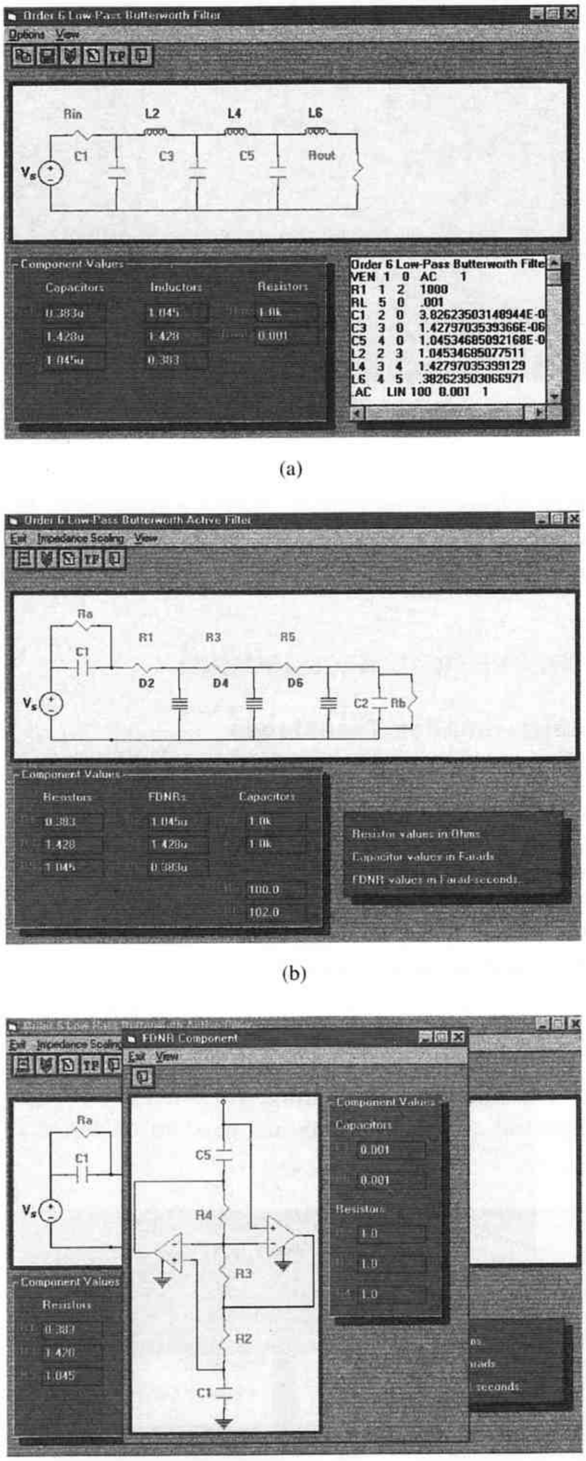
C	1u	R1	134.416
		R3	134.416
		Ro	1.0
		R8	3.194k
		R4	7.607k
		R5	2.375

Configurations

- ● Sallen-Key
- ○ GIC
- ● State Variable
- ● Tow Thomas
- ● Sallen Key [*]
- ● Twin T
- ● 1 Order OA[a]
- ● 1 Order OA[b]
- ● 1 Order RC
- ● Multiple Feed Back

Stage 1

Figure 6 Active hardware realization of the first biquadratic factor. Here, we show a GIC-based biquad realization. When choosing another stage, the user can change to another realization for the following stages, if desired. The subwindow shows the color code for resistor R_8.



Order 6 Low Pass Butterworth Filter

Component Values

Capacitors	Inductors	Resistors
0.383u	1.045	1.0k
1.428u	1.428	0.001
1.045u	0.383	

```
Order 6 Low-Pass Butterworth Filte
VEN  1  0  AC     1
R1   1  2  1000
RL   5  0  .001
C1   2  0  3.82623503148944E-0
C3   3  0  1.42797035393366E-06
C5   4  0  1.04534685092168E-0
L2   2  3  1.04534685077511
L4   3  4  1.42797035399129
L6   4  5  .382623503066971
.AC   LIN 100  0.001  1
```

(a)

Order 6 Low-Pass Butterworth Active Filter

Component Values

Resistors	FDNRs	Capacitors
0.383	1.045u	1.0k
1.428	1.428u	1.0k
1.045	0.383u	
		100.0
		102.0

Resistor values in Ohms
Capacitor values in Farads
FDNR values in Farad-seconds

(b)

FDNR Component

Component Values

Capacitors
0.001
0.001
Resistors
1.0
1.0
1.0

Component Values

Resistors
0.383
1.420
1.045

(c)

Figure 7 (a) Passive ladder realization of a sixth-order lowpass Butterworth filter. (b) Ladder Butterworth filter after performing a Bruton transformation. Resistors have been changed to capacitors, inductors to resistors, and capacitors to frequency-dependent negative resistors (FDNRs). (c) Realization of the FDNRs by generalized immitance converters (GICs).

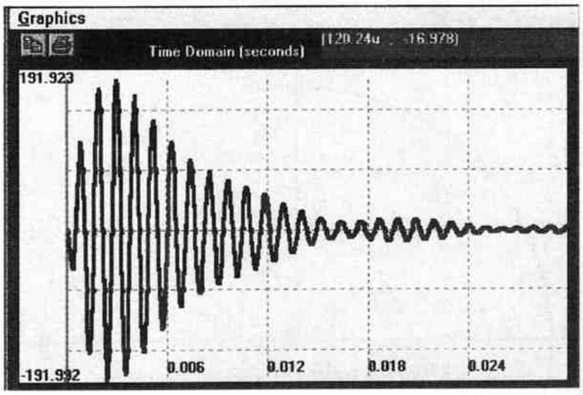
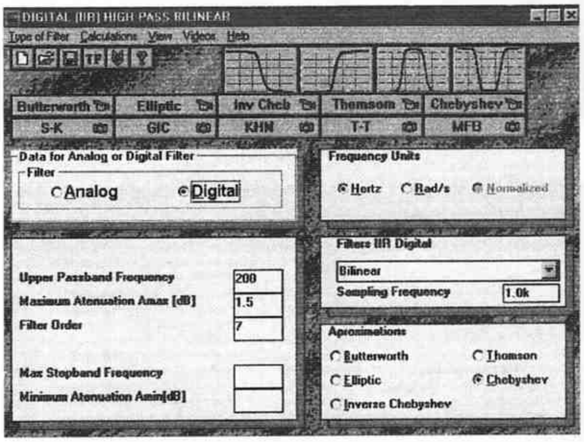


Figure 8 Impulse response of a bandpass Butterworth filter.

imposed by the transfer function will the allow either to obtain a passive realization or it will be indicated what steps to take to get a realization. For example, it is well known [4] that even-order Chebyshev filters cannot have equal terminating resistances. If the user inadvertently chooses that option, WinFiltros will require the user to enter another set of terminating resistances so that a realization is obtained. There is also the option to obtain an active realization by replacing the grounded inductors in a highpass filter by a simulated inductor using a generalized immitance converter (GIC) for each one, and for lowpass filters by performing the Bruton transformation and using a GIC for the grounded frequency-dependent negative resistors (FDNRs).



Data for Analog or Digital Filter

Filter: ○ Analog ● Digital

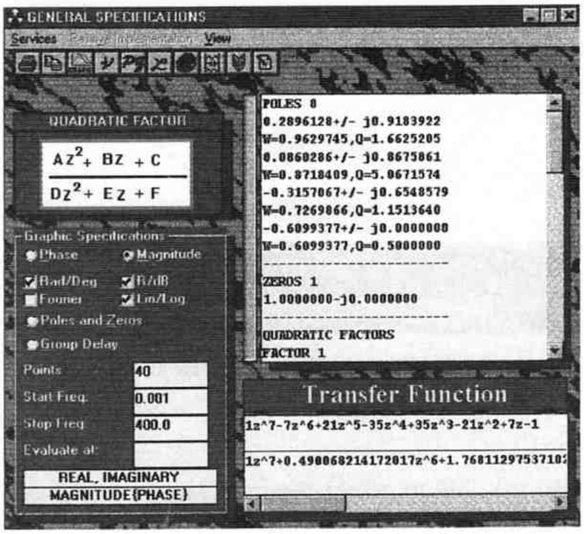
Frequency Units: ● Hertz ○ Rad/s ● Normalized

Upper Passband Frequency: 200
Maximum Atenuation Amax [dB]: 1.5
Filter Order: 7
Max Stopband Frequency:
Minimum Atenuation Amin[dB]:

Filters IIR Digital: Bilinear
Sampling Frequency: 1.0k

Aproximations: ○ Butterworth ○ Thomson ○ Elliptic ● Chebyshev ○ Inverse Chebyshev

Figure 9 Input window for the design of a Chebyshev digital filter. Here, we see that a new subwindow is enabled, allowing the user to give a sampling frequency and to select a transformation from the *s*-plane to the *z*-plane. The default transformation is bilinear.



● Phase ● Magnitude
☑ Rad/Deg ☑ R/dB
☐ Fourier ☑ Lin/Log
● Poles and Zeros
● Group Delay

Points: 40
Start Freq: 0.001
Stop Freq: 400.0
Evaluate at:

```
POLES 8
0.2896128+/- j0.9183922
W=0.9629745,Q=1.6625205
0.0860286+/- j0.8675861
W=0.8718409,Q=5.0671574
-0.3157067+/- j0.6548579
W=0.7269866,Q=1.1513640
-0.6099377+/- j0.0000000
W=0.6099377,Q=0.5000000
------------------------
ZEROS 1
1.0000000-j0.0000000
------------------------
QUADRATIC FACTORS
FACTOR 1
```

```
1z^7-7z^6+21z^5-35z^4+35z^3-21z^2+7z-1
1z^7+0.490068214172017z^6+1.76811297537101
```

Figure 10 Output window for the digital Chebyshev filter designed.

Active Filters

The cascade approach is used for active filter design. There are several available topologies for the biquad stages: Sallen and Key, multiple feedback (including the Friend biquad), state-variable KHN, Tow-Thomas, GIC-based biquad, and twin-T [4–6].

Frequency Response

It is possible to obtain poles, zeros, quadratic factors, and the numerator and denominator polynomials for the transfer function, magnitude, phase, and group delay plots, as well as a pole-zero plot. It is

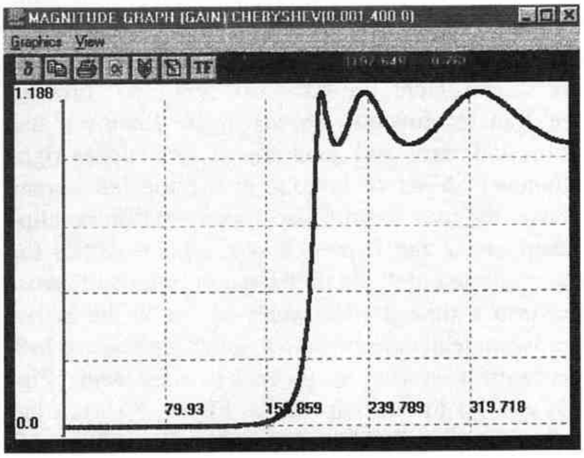
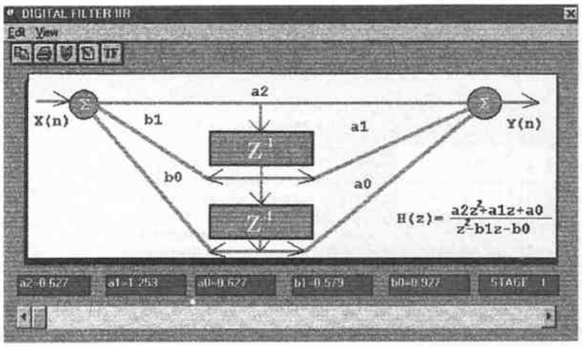


Figure 11 Magnitude response plot for the digital Chebyshev filter. The equal ripple characteristic can be clearly observed.



a2=0.627 a1=1.253 a0=0.627 b1=0.579 b0=0.927 STAGE 1

Figure 12 Realization of the first biquadratic stage for the digital Chebyshev filter.

also possible to obtain a numerical evaluation for the transfer function magnitude.

Time Domain Response

Impulse and step responses are also available for the filter designed. This is done by taking the inverse Laplace transform of the transfer function obtained in the approximation step multiplied by a step or an impulse excitation.

EXAMPLES

In this section, we will show several examples representative of the kind of information that can be obtained from WinFiltros. After clicking on the WinFiltros icon, we go to the first window as shown in Figure 1, where the user can choose which kind of filter he intends to design.

As our first example, we will show how to obtain an elliptic bandpass filter. Figure 2 shows the window where the input specifications are given, while Figure 3 shows the window where the output data are shown. Here, we have two windows showing the transfer function (lower right window) and poles and zeros and quadratic factors (upper right window). A set of buttons in the top left corner allows the user to print data, copy data to the clipboard, make the requested plot, obtain values for the requested plot, obtain the list of poles and zeros, perform a time domain analysis, go to the active hardware realization window, go to the passive ladder realization window, go back to main menu (Fig. 2), and go to the help menu. Figure 5 shows the pole-zero plot for the elliptic bandpass filter designed. Any one of these poles can be shifted by capturing it with the mouse's right button, and the effect can be observed in, for example, the magnitude plot. For example, if one desires to see what effect on the transfer function a pole has, it is first necessary to plot the magnitude response followed

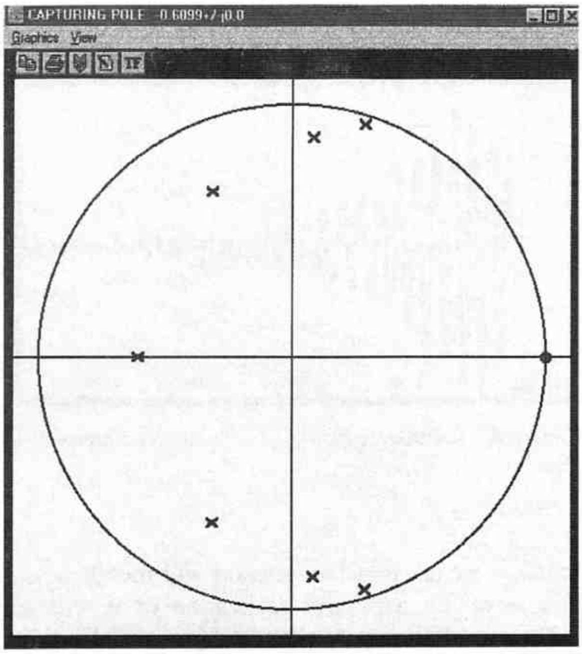
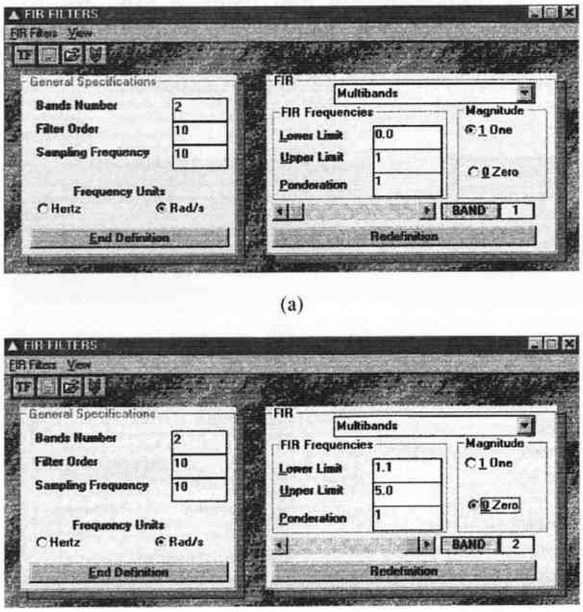


Figure 13 Pole-zero plot for the digital filter designed. Here, we see that the poles are located inside the unit circle and that all of the zeros are located at $z = 1$; that is, they are located at DC.



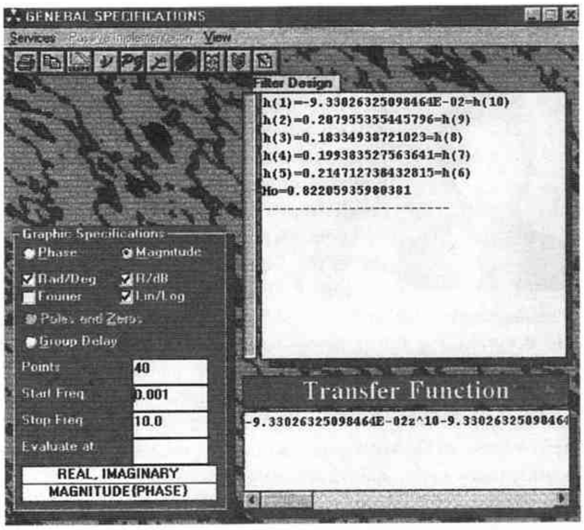
General Specifications
Bands Number 2
Filter Order 10
Sampling Frequency 10
Frequency Units ○ Hertz ● Rad/s
FIR Multibands
FIR Frequencies
Lower Limit 0.0
Upper Limit 1
Ponderation 1
Magnitude ● 1 One ○ 0 Zero
BAND 1

(a)

General Specifications
Bands Number 2
Filter Order 10
Sampling Frequency 10
Frequency Units ○ Hertz ● Rad/s
FIR Multibands
FIR Frequencies
Lower Limit 1.1
Upper Limit 5.0
Ponderation 1
Magnitude ○ 1 One ● 0 Zero
BAND 2

(b)

Figure 14 (a) Input window for an FIR filter design. The definition is shown for the bandpass. (b) Definition of the stopband.



```
h(1)=-9.33026325098464E-02=h(10)
h(2)=0.207955355445796=h(9)
h(3)=0.18334938721023=h(8)
h(4)=0.199383527563641=h(7)
h(5)=0.214712738432815=h(6)
Ho=0.82205935980381
------------------------
```

Points 40

Start Freq 0.001

Stop Freq 10.0

Evaluate at

```
-9.33026325098464E-02z^10-9.33026325098464
```

Figure 15 Output window for the FIR filter designed.

by the pole-zero plot, capturing the pole with the mouse's right button and shifting it to a new location. The modified magnitude plot will appear on the screen. Figure 6 shows a hardware realization for one of the biquad stages in a cascade realization. Here, we show a GIC-based biquad. Giving an initial value for capacitor C, WinFiltros gives the remaining values of the components. By clicking on any of the resistor values, a subwindow is opened showing the color code for it. In our example, it is done for resistor R_8.

Our second example shows a Butterworth lowpass filter, which in this case is realized as a ladder lowpass filter. Figure 7(a) shows the window for this passive ladder filter realization, and Figure 7(b) shows the realization with FDNRs obtained after realizing a Bruton transformation [4], including resistors R_a and R_b needed to obtain correct behavior at DC [4]. By clicking on any of the FDNRs, we obtain in Figure 7(c) an active realization with GICs [4,6].

As our third example, we show the impulse response plot for a bandpass Butterworth filter (Fig. 8).

Another example is the design of a digital Chebyshev highpass filter using bilinear transformation. There is also the possibility of using either backward or forward transformations (Fig. 9). Comparing the windows in Figure 2 and 9, we see that for digital filters a subwindow appears where we can choose the transformation desired and the sampling rate. Figure 10 shows the window with the poles, zeros, quadratic factors, and a transfer function. Here, we also have available the same set of buttons in the top left corner as in the analog case. The magnitude plot for this filter is presented in Figure 11. Figure 12 shows a biquad stage for the digital filter designed. Figure 13 shows the pole zero plot.

The last example shows an FIR filter designed by the Parks method. Figure 14 shows the input window for a two-band filter with a lowpass characteristic. Figure 14(a) shows the passband definition, and Figure 14(b) shows the stopband definition. Figure 15 shows the result window with the transfer function and the coefficients of the transfer function.

CONCLUSIONS

In this article we presented a description of a software package that can be used to design analog and digital filters, called Multimedia WinFiltros. This package can be used in the classroom or by practicing engineers. It is very user-friendly and can be used with any IBM-compatible computer with Windows (version 3.1 or higher). Videos and oral explanations are available to complement theoretical background. Several examples showing the use of the software were presented.

ACKNOWLEDGMENT

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BIOGRAPHIES

David Báez López received the BS degree in physics with honors from the Autonomous University of Puebla, Mexico, in 1973, and MS and PhD degrees in electrical engineering from the University of Arizona, Tucson, in 1976 and 1979, respectively. From 1979 to 1984, he was researcher with the Instituto Nacional de Astrofísica Optica y Electrónica, Tonantzintla, Mexico, and became head of the Department of Electronics in 1983. In 1985 he joined the Department of Electrical Engineering of the Universidad de las Américas–Puebla, Mexico, where he is currently a professor, and he was department chairman from 1988 to 1996. His interests are in the areas of education on circuits and systems, active filters, and digital image processing. He was the general chairman of the IEEE MEXICON'94 conference and is founder of the International Conference on Electronic Engineering, held in Puebla, Mexico, every other year. He has published over 30 papers in journals and conference proceedings and is author of the book *Circuit Analysis Using SPICE,* published in 1995 in Mexico by Ediciones Alfaomega (in Spanish).

R. Jaroszynsky received the BS and the MS degrees in electronic engineering from Universidad de las Américas–Puebla. He was an independent consultant in computer systems in Mexico prior to establishing residence in Poland, where he works with Optimus–Seko in automation and visualization of industrial processes.

Pablo Martínez was born in Puebla, Mexico, on March 15, 1973. He received a BS degree in computer engineering from Universidad de las Américas–Puebla in 1996. He worked in computer networks in the Volkswagen plant in Mexico. He later joined Kautex Textron, a German company dedicated to the manufacturing of fuel tanks, and has worked in its Indiana, Windsor, and Bonn plants. Currently, he is working in the installation of the Puebla factory of this company. In his leisure time, he works intensely with the Mexican branch of the Boys Scouts.

Juan Manuel Ramírez received his BS degree from the Instituto Politécnico Nacional, Mexico, in 1979; the MS degree from the Instituto Nacional de Astrofísica, Optica y Electrónica, Mexico, in 1983; and the PhD degree from Texas Tech University in 1991, all in electrical engineering. He is a professor at the Department of Electrical Engineering, Universidad de las Américas–Puebla, Mexico, where from 1986 to 1988 he served as chairman. He is currently a full professor and has been serving a second term as chairman since 1996. He was the general chairman of the International Conference on Electronics, Communications, and Computers (CONTELECOMP'95), Puebla, Mexico. His research interests include signal and image processing, neural networks, fuzzy logic, and pattern recognition.

Guillermo Espinosa Flores-Verdad received the BS degree from Universidad Autonoma de Puebla, Mexico, in 1980, the MS degree from Instituto Nacional de Astrofísica, Optica y Electrónica (INAOE), Mexico, in 1983, and the PhD degree from University of Pavia, Italy, in 1989, all in electronics. He worked as an assistant professor at Universidad Autonoma de Puebla from 1983 to 1985 and at INAOE previous to his doctoral work. From 1990 to 1993 he was group leader at SGS–Thomson Microelectronics Corp. in the Central R&D Department in Milano, Italy. Since 1993 he has been working at INAOE, where he is cofounder of the PhD program in electronics. His interests involve research on the design of analog and mixed mode IC in CMOS and BiCMOS technologies, such as switched-capacitor circuits, current-mode, and continuous time circuits, as well as A/D and D/A converters working at low voltage and low power. He is also interested in the development of CAD for design automation going from circuit design to layout design.

G. Cabrera, G. Reyes, and J. Luna *(Biographical sketches and photographs not available.)*