MIPRO 2011, May 23-27, 2011, Opatija, Croatia

Power Consumption, Noise and Bode Diagram Measurement of Active Filters

Drazen Jurisic*, Neven Mijat* and Miro Ranilovic**
* University of Zagreb/Faculty of electrical engineering and computing, Unska 3, Zagreb, 10000, Croatia
** Ericsson Nikola Tesla, Krapinska 45, Zagreb, 10000, Croatia
Phone: (+385 1) 612 99 41 Fax: (+385 1) 612 96 52 E-mail: drazen.jurisic@fer.hr

Abstract - This paper presents the measurement methods of power consumption, output noise spectrum and Bode diagram. The power consumption is measured through supply current using a 'FLUKE 289 True RMS Multimeter'. The output thermal noise spectral density and Bode diagrams are measured using high-quality equipment consisting of 'Network Analyzer HP 4195A' and computer. The measured data are downloaded from Network Analyzer using GPIB interface bus and Matlab. The measured diagrams are plotted using HPGL format generated by Network Analyzer. The measurements are demonstrated on different examples of fourth-order band-pass (BP) active-*RC* filters realizations. The devices under measurement were realized using printed circuit boards. It was shown that the new design of filters with single amplifier shows better performance both regarding power consumption and noise than the cascade design.

Active-RC Filters, Band-Pass Filters, Measurement of Power Consumption Noise and Bode diagrams, GPIB bus.

I. Introduction

In this paper we present the measurements of power consumption, output noise spectrum and transfer function magnitude (Bode plot) of active-RC filters using laboratory equipment. It is also shown how to use Matlab with GPIB interface bus to download the measured data and process them on the computer. The measurements are demonstrated on the new single-amplifier band-pass (BP) active-RC filters [1]–[3] that have better performance than the standard cascaded-Biquads BP filters. In the measurements high-quality equipment was used, such as Network Analyzer HP 4195A and FLUKE 289 True RMS Multimeter.

A procedure for the new design of low-sensitivity, low-noise and low-power (second- to eighth-order) allpole BP active-*RC* filters was presented in [1]–[3]. The filters use only one operational amplifier and a minimum number of passive components. The advantages of the newly-designed single-amplifier filters compared to other designs, e.g. the cascade of Biquads are: *i*) lower noise; *ii*) lower power consumption; *iii*) lower number of components. The low sensitivity, low power consumption, and low noise features of the resulting circuits, as well as low component spread, are demonstrated for the case of a fourth-order filter example.

This work has been financially supported by The National Foundation for Science, Higher Educations and Technological Development of the Republic of Croatia.

Using PSpice [4] with a TL081 opamp model, the filter performance was simulated in [1]–[3] and the results compared and verified with measurements of a discrete-component printed-circuit-board version of these filters in this paper. Measured and simulated results show a good agreement.

Measurements were made on a cascaded-Biquad filter and a single–amplifier filter, where both were realized on separate printed circuit boards. Discrete 1% accurate capacitors and resistors (E24 series) were used together with the TL081 Texas Instruments JFET input opamp.

II. Low-noise, Low-Sensitivity Circuits

A new and straightforward method of designing voltage-mode active RC band-pass (BP) filters of relatively high order, using only one operational amplifier was developed for applications primarily using discrete components, in which power consumption is critical. To keep the cost of the filters low, it is desirable to avoid the need for filter tuning, and this is possible only for filters of medium to low selectivity, and low sensitivity to component tolerances.

Fortunately the RC ladder nature of the resulting circuits permits a recently introduced scheme of "impedance tapering" [5] which in many cases can reduce the sensitivity to component tolerances sufficiently to eliminate the need for tuning. Furthermore, it has been shown in [6] that using the impedance tapering design method, the output thermal noise of single-amplifier active-RC filters with ladder feedback networks is also minimized, when compared with standard design methods.

III. Measurements

A. *Measurement of the output noise spectrum and transfer-function magnitudes*

Measurements were made on: *i*) a single-amplifier filter with components given in Table 1 and shown in Figure 1; and *ii*) a cascaded-Biquad filter amplifier filter with components given in Table 2 and shown in Figure 2, where both were realized on separate circuit boards (see Figure 3(a) and (b), respectively). The two filter boards that were built and measured realize a BP transfer function with amplitude response having a 5 kHz center frequency and 6 kHz bandwidth (see Figure 5).

TABLE I. ELEMENT VALUES FOR THE 'IMPEDANCE-TAPERED' SINGLE-AMPLIFIER FOURTH-ORDER BAND-PASS FILTER IN FIGURE 1; R[Ω]; C[nF]; R_G=10kΩ.

MODE	R'_1	R''_1	C_1	R_2	C_2	R_3	C_3	R_4	C_4	R_F	C_{TOT}
Normalized	2.93275	1.5174	1	0.830938	1.20346	1	1	3.32375	0.300865	1.18875	3.5043
f_0=5kHz	933.5	483.0	100	264.5	120.3	318.3	100	1058.0	30.08	11.88 k	≈350

TABLE II. ELEMENT VALUES FOR THE TWO-BIQUAD CASCADE REALIZATION OF THE FOURTH-ORDER BAND-PASS FILTER IN FIGURE 2; R[Ω]; C[nF]; R_{GA}=R_{GB}=10kΩ.

MODE	R'_{1A}	R''_{1A}	R_{2A}	C_{1A}	C_{2A}	R_{FA}	R'_{1B}	R''_{1B}	R_{2B}	C_{1B}	C_{2B}	R_{FB}
Normalized	2.06069	0.740453	0.391462	1	1.39151	2.78302	3.11592	4.46849	1.31929	1	1.39151	5.7741
f_0=5kHz	895.28	321.69	170.074	73.26	101.95	27.83k	1353.74	1941.37	573.176	73.26	101.95	57.74k

Both realizations have four capacitors (for the fourth-order filter) and the total capacitance is 350nF. The remaining circuitry contains resistors and operational amplifiers that generate noise. The noise of the single-opamp BP filter is reduced by the application of impedance tapering. The Biquads in cascade are designed for "optimum" performance and there is no way to reduce their noise further. Thus, a comparison of the *optimized* single-opamp BP filter to the *optimized* cascade of BP Biquads is made.

For each filter the output noise spectral density was measured in the set up shown in Figure 4(a). The measurement equipment consisted of a high-quality HP 4195A Network Analyzer, which measures the spectrum of signals and/or noise (when in the Spectrum mode), and Bode diagram (when in the Network mode). A high-impedance input HP 41800A active probe provided exact measurements without overloading the filter's output. A battery power supply was used in order to guarantee a noiseless supply voltage, and a grounded metal shield surrounded the filter board in order to minimize outside interference. The measured output- noise spectral-density runs are shown in Figure 6(a) and (b). Note that the $1/f$ noise is too low to appear in the measurements. The thermal (Johnson) noise is apparent at higher frequencies, especially around the center frequency of 5 kHz. Comparing the measured results presented in Figure 6(a) and (b) with the results obtained from the PSpice simulation with a TL081 opamp model [4], shows very good agreement between the two. The measured output noise of the new tapered single-amplifier fourth-order BP filter is reduced when compared to a conventional cascade design.

The filter amplitude response measurements were made using the set up shown in Figure 4(b). Comparing the measurements shown in Figure 5 with the simulations obtained using PSpice [4]; we again found very good agreement between the two. The explanation of the cable connections of the amplitude response measurement is shown in Figure 7, where the 50Ω terminations and power splitter function are explained.

B. *Power consumption: single-amplifier BP filter versus two-biquad cascade*

For the tapered single-amplifier and cascaded-Biquad fourth-order BP filters above, the power consumption is measured in the arrangement shown in Figure 8.

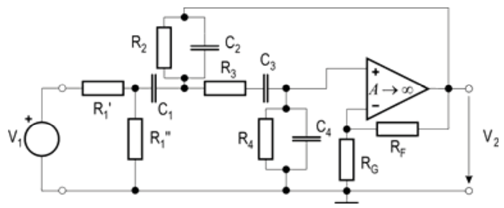

Figure 1. Single-amplifier fourth-order BP filter circuit (Table 1).

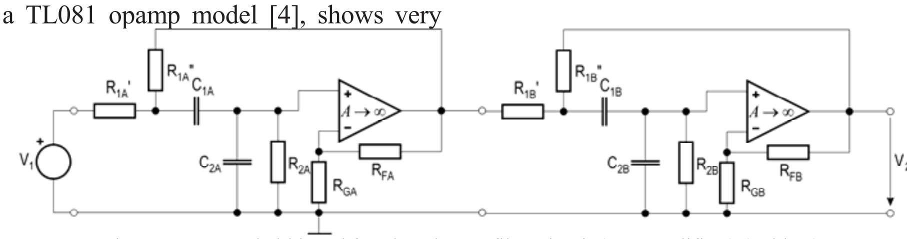

Figure 2. Cascaded-biquad fourth-order BP filter circuit (two amplifiers) (Table 2).

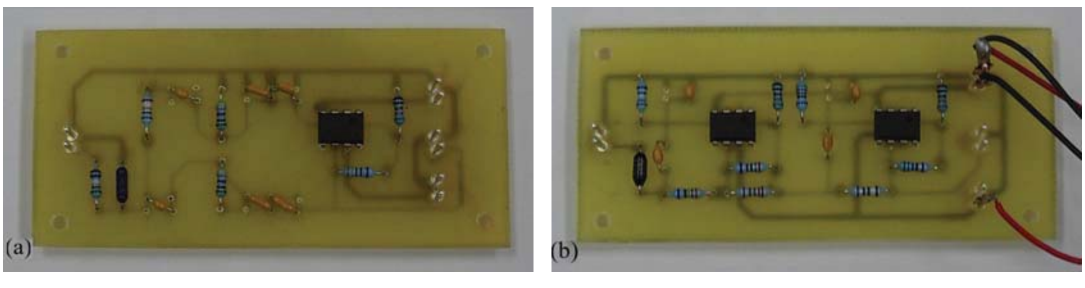

Figure 3. Discrete-component filter realized on printed circuit board. (a) Single-amplifier filter. (b) Cascaded-biquad two-amplifier filter.

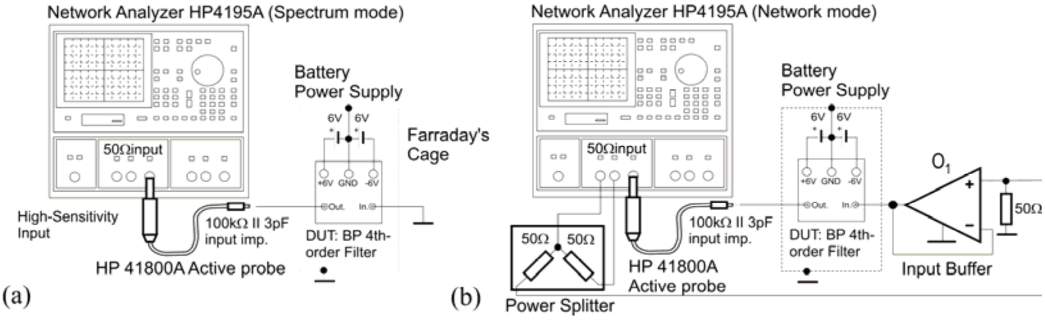

Figure 4. Measurement set up for fourth-order BP filter: (a) Filter output-noise spectral density measurement setup. (b) Filter transfer-function magnitude measurement setup.

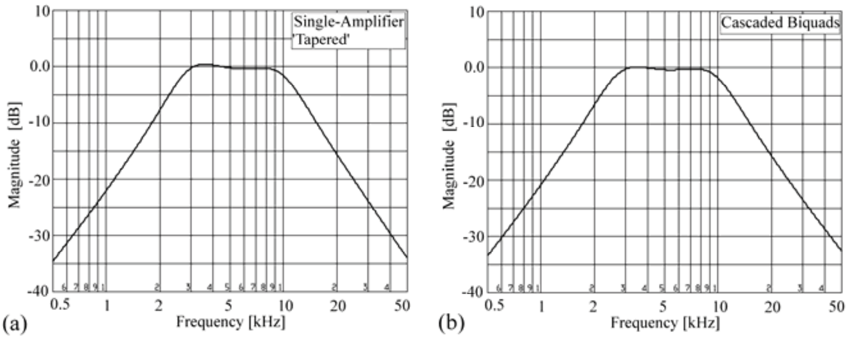

Figure 5. Measured amplitude response of fourth-order band-pass filter realized by: (a) Single-amplifier 'tapered' filter. (b) Cascaded Biquads.

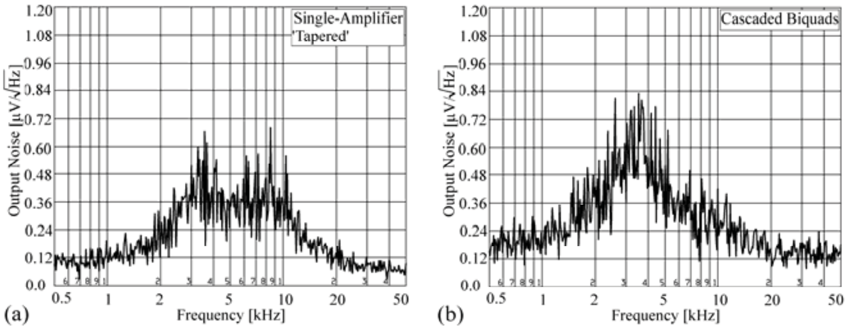

Figure 6. Measured output noise spectral density of filters: (a) Single-amplifier 'tapered' filter. (b) Cascaded Biquads.

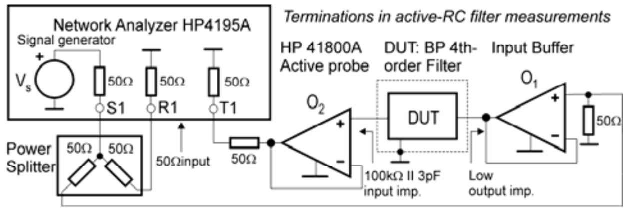

Figure 7. 50Ω terminations in filter transfer-function magnitude measurement setup in Figure 4(b).

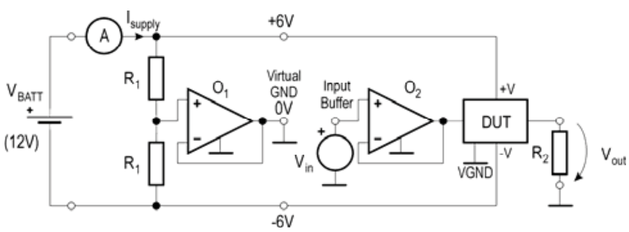

Figure 8. Schematic of power consumption measurement of the active-*RC* filter as device under test (DUT).

The power supply (12V battery) is asymmetrical but made symmetrical with the help of two resistors (R_1=1MΩ), and the voltage follower using opamp O_1 provides a virtual ground (0V). The buffer voltage follower O_2 provides input isolation and ensures proper functioning of the filter. The signal generator V_{in} (50Ω) generates a sinusoidal signal of 1V amplitude and 5kHz frequency (center frequency of the filters). The loading resistance R_2 is high (≈10MΩ) and can be neglected. The devices under test (DUTs) are the two active-*RC* filter realizations using discrete components shown above. The main contribution to the power consumption is from the quiescent opamp currents and the loading RC feedback networks. The supply current (I_{supply}) is measured using a 'FLUKE 289 True RMS Multimeter' (A). The measurements show 4.65mA (RMS) for the single-opamp filter and 6.26mA for the cascade filter. As expected our new single-opamp filter requires lower power than the Biquad cascade.

C. *Transfer of the measured data using GPIB interface bus from Network Analyzer to computer*

To transfer the measured data from the HP 4195A Network Analyzer to the computer we use Matlab. The connection is performed through HP/Agilent USB-GPIB interface 82357A. Two Matlab m-files are used to initialize, and then to transfer, the measurement data over the GPIB interface bus. The initialization m-file is shown in Figure 9. It returns the 'obj1' object into Matlab's workspace. The measurement m-file is listed in Figure 10.

```
function [obj1] = ConfigureHPIB
% Create a GPIB object.
obj1 = instrfind('Type', 'gpib', 'BoardIndex',
7, 'PrimaryAddress', 17, 'Tag', '');
% Create the GPIB object if it does not exist
% otherwise use the object that was found.
if isempty(obj1)
    obj1 = gpib('AGILENT', 7, 17);
% Default HPIB address of analyzer is 17
else
    fclose(obj1);
    obj1 = obj1(1);
end
obj1.InputBufferSize = 102400
%--InputBufferSize check
% Connect to instrument object, obj1
fopen(obj1);
% Communicating with instrument object, obj1
fprintf(obj1, 'ID?');
data1 = fscanf(obj1, '%c', 512);
data1
% If the analyzer is successfully connected it
would answer on the command 'ID?' with its name
% Measurement parameters setup %
fprintf(obj1, 'CLS');
fprintf(obj1, 'FNC1'); %Spectrum analyzer;
selects the Network configuration
fprintf(obj1, 'START=0.5K'); % Start sweep freq.
fprintf(obj1, 'STOP=50K'); % Stop sweep freq.
fprintf(obj1, 'SWT2'); % Sweeps logarithmic step
fprintf(obj1, 'SWM2'); % Selects single sweep
fprintf(obj1, 'AUTO'); % Changes the display
scale properly to the data
fprintf(obj1, 'ST?');  % Sweep Time reg?
data1 = str2num(fscanf(obj1));
timeneeded=data1        % Timeneeded is the time
needed for one sweep in seconds
disp('Analyzer is successfully initialized.');
```

Figure 9. Matlab file 'ConfigureHPIB.m'.

```
function MeasureHPIB (obj1, WorkspaceName)
fprintf(obj1, 'CLS'); % Clear Status Byte
fprintf(obj1,'RQS=2');% Bitmask for SRQ-Error
pause(3);
% Start one sweep
fprintf(obj1,'SWTRG');% Trigger - resets the
sweep measurement and restarts the sweep
fprintf(obj1, 'AUTO');% Auto Scale
fprintf(obj1, 'CLS'); % Clear Status Byte
% reading registers
fprintf(obj1, 'X?');  % X: values frequencies;
data_X =fscanf(obj1); % IEEE 64-bit double prec.
fprintf(obj1, 'A?');  % A: values amplitude dB
data_A =fscanf(obj1); % IEEE 32-bit double prec.
fprintf(obj1, 'B?');  % B: values phase in deg
data_B = fscanf(obj1);% IEEE 32-bit double prec.
fprintf(obj1, 'AUTO');% Autoscale
ampl1 = str2num(data_A);
phase1 = str2num(data_B);
freq1 = str2num(data_X);
save(WorkspaceName,' ampl1',' phase1',' freq1')
% hpgl plot
fprintf(obj1, 'PSCALE=2000,800,9200,7208');
% Enters plot size data
fprintf(obj1, 'SCLP1'); % Specifies the plotting
area by all display area
fprintf(obj1, 'CPYM1'); % Selects plot hardcopy
mode (HPGL)
fprintf(obj1, 'COPY');  % Starts or aborts the
hardcopy operation
hpgldata1=fscanf(obj1); % Save HPGL into file
named filename1.hgl
fiddata = fopen('filename1.hgl', 'wt');
fprintf(fiddata, '%s', hpgldata1);
fclose(fiddata);
figure;  % Drawing figure in Matlab
semilogx(freq1, ampl1);
xlabel('Frequency, Hz');
ylabel('Magnitude, dB');
title('Bode plot');
```

Figure 10. Matlab file 'MeasureHPIB.m'.

Using the two .m routines above, all the measurement data have been transferred from the HP 4195A Network Analyzer to Matlab, resulting in Figures 5 and 6 in this paper.

IV. Conclusions

In this paper we have presented the measurement of discrete-component active-RC filters using a typical university lab environment. We have demonstrated how to measure power consumption, noise and Bode diagrams using high-quality laboratory equipment. The measurements have been demonstrated with the example of two BP active-RC filters that realize the same transfer function magnitude, but have different performance. The amplitude-response measurement has confirmed that the filters realize the same BP transfer function. Furthermore, it was clearly demonstrated that the advantages of the newly-designed optimum single-amplifier filters, compared to the cascade of biquads, have: *i*) lower noise; *ii*) lower power consumption; *iii*) a lower number of components. On the other hand, the two designs are similar in terms of their sensitivity to component tolerances. Considering all the performance characteristics, the new design technique clearly demonstrates an improvement over other design techniques.

References

[1] D. Jurisic and N. Mijat, “Use of "Lossy" LP-BP-Transformation in Active Second-order BP Filter Design Procedure,” Proceeding of IEEE International Symposium on Image and Signal Processing and Analysis ISPA, Pula, Croatia, 2001, pp. 491–495.

[2] D. Jurisic, N. Mijat and G. S. Moschytz, “Design of Fourth-Order BP Active-RC Filters Using a "Lossy" LP-BP Transformation,” Proceeding of IEEE European Conference on Circuit Theory and Design ECCTD, Espoo, Finland, 2001, pp. 117–120.

[3] D. Jurisic, G. S. Moschytz and N. Mijat, “Low-Sensitivity, Low-Power Fourth-Order Band-Pass Active-RC Allpole Filter Using Impedance Tapering,” Proceeding of International IEEE Conference on Electronics, Circuits, and Systems ICECS, Msida, Malta, 2001, pp. 815–818.

[4] PSpice Circuit Analysis - Users Manual, Microsim Corporation, Irvine CA-USA, 1996.

[5] G. S. Moschytz, “Low-Sensitivity, Low-Power, Active-*RC* Allpole Filters Using Impedance Tapering,” IEEE Transactions on Circuits and Systems Part II, vol. 46, pp. 1009–1026, Aug 1999.

[6] D. Jurisic, G. S. Moschytz and N. Mijat, “Low-noise, low-sensitivity, active-RC allpole filters using impedance tapering,” International Journal of Circuit Theory and Applications, Early View, doi: 10.1002/cta.740 (accepted for publication).