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3. Numerical Simulation

In this section we will use MATLAB to generate a numerical simulation of the transfer function derived above. Firstly we must derive the transfer function and then plot the magnitude response on a bode plot. This is done using the code that can be seen in the appendix of this report. The code generates the following plot on which the centre frequency for the filter is displayed.

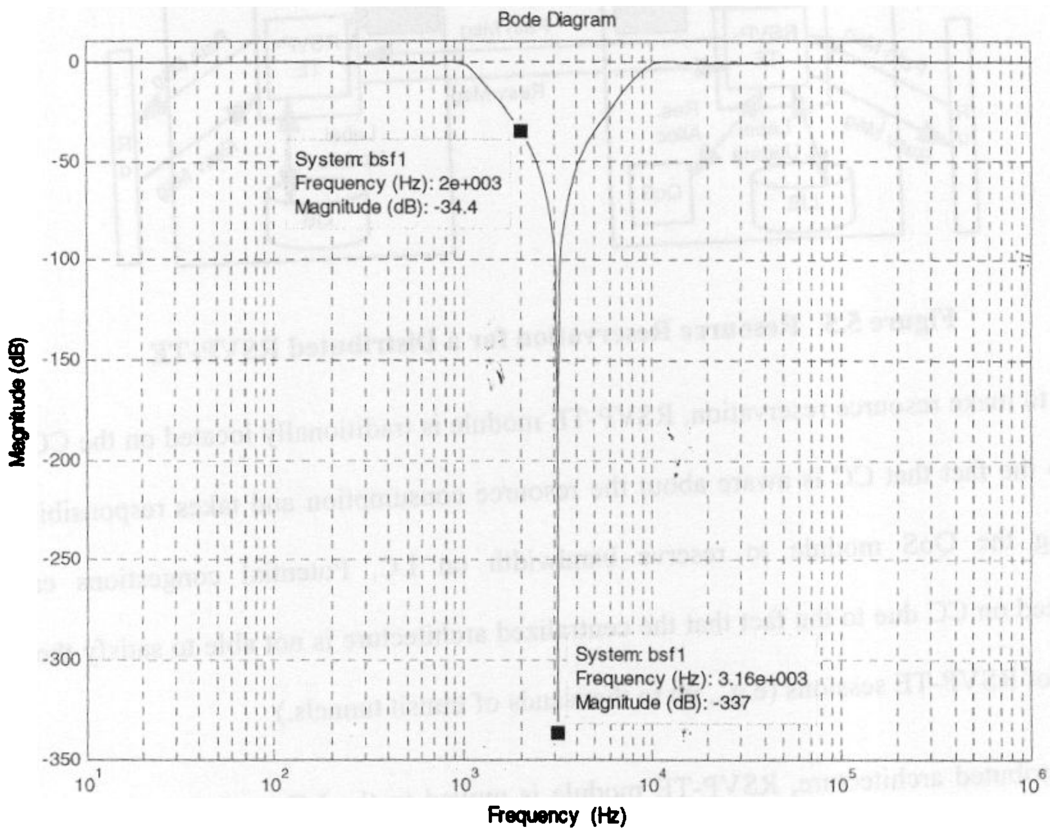

Figure 1: Numerical Simulation Results (MATLAB)

From this graph we can see that the centre frequency is indeed as expected, i.e. 3162.2777Hz as calculated in the previous section of the report. If we take the cursor along the pass bad we can also indeed see that there is a 1 dB ripple, as expected. Furthermore we see that the required attenuation at 2 kHz is satisfied.

Following this we wish to verify that the cut-off frequencies, and hence bandwidth of the stop band, are indeed what we expect them to be, i.e. 1 kHz ad 10 kHz. To do this we can use the MATLAB command "bandwidth" on our transfer function which will give us the first cut-off frequency this command yields $6.7561*10^3$ rad/s which is equivalent to 1075.2619 Hz. From this since the numerical simulation is

4.1 Sample Design Calculations

We take one of our second order transfer functions that were given in section 2 of the report. One can be seen below.

$$|H_2(s)| = \frac{s^2 + 3.948 * 10^8}{s^2 + 2.552 * 10^4 s + 3.901 * 10^9}$$

Comparing this to the transfer function to the general one shown above, we can immediately see that the first order "s" term in the numerator is equal to zero. This implies that:

$$\frac{R_8}{R_6} = \frac{R_1 R_8}{R_4 R_7}$$

To satisfy this we can do the following:

$$R_8 = R_6 = R_4 = R_7 = 1\Omega$$

Following this we can see that:

$$\frac{1}{R_1 C_1} = 2.552 * 10^4$$

Taking R_1 to be 1Ω, we can then obtain C_1

$$\frac{1}{C_1} = 2.552 * 10^4 \rightarrow C_1 = 39.185\mu F$$

Also

$$\frac{R_8}{R_3 R_5 R_7 C_1 C_2} = 3.948 * 10^8$$

With $R_5 = 1\Omega$ we can then get:

$$C_2 = \frac{1}{C_1 3.948 * 10^8} = \frac{1}{(39.185\mu)(3.948 * 10^8)} = 64.64\mu F$$

Finally,

$$\frac{R_8}{R_2 R_3 R_7 C_1 C_2} = 3.901 * 10^9 \rightarrow R_2 = \frac{1}{(C_1 C_2) 3.901 * 10^8} = .1012\Omega$$

Following similar calculations we can also obtain capacitor and resistor values for the other filter stages. The values will be tabulated in the following section.

4.2 Ideal Values Simulation

In order to ensure that our design is correct we will simulate the circuit using the calculated ideal component values as calculated in the previous section. These calculated values can be seen in the table shown below:

Table 1: Calculated Values for Cascaded Fleischer-Tow Filters

Stage 1				Stage 2				Stage 3			
R1	1Ω	C1	8.7336 µF	R1	1Ω	C1	39.185 µF	R1	1Ω	C1	387.1 µF
R2	1Ω	C2	0.29 mF	R2	0.1012 Ω	C2	64.64 µF	R2	9.8824 Ω	C2	6.5433 µF
R3	1Ω			R3	1Ω			R3	1Ω		
R4	1Ω			R4	1Ω			R4	1Ω		
R5	1Ω			R5	1Ω			R5	1Ω		
R6	1Ω			R6	1Ω			R6	1Ω		
R7	1Ω			R7	1Ω			R7	1Ω		
R8	1Ω			R8	1Ω			R8	1Ω		

For this section we will use ideal VCVS to simulate the op-amps. Plugging the values into the three structures we obtain the following circuits:

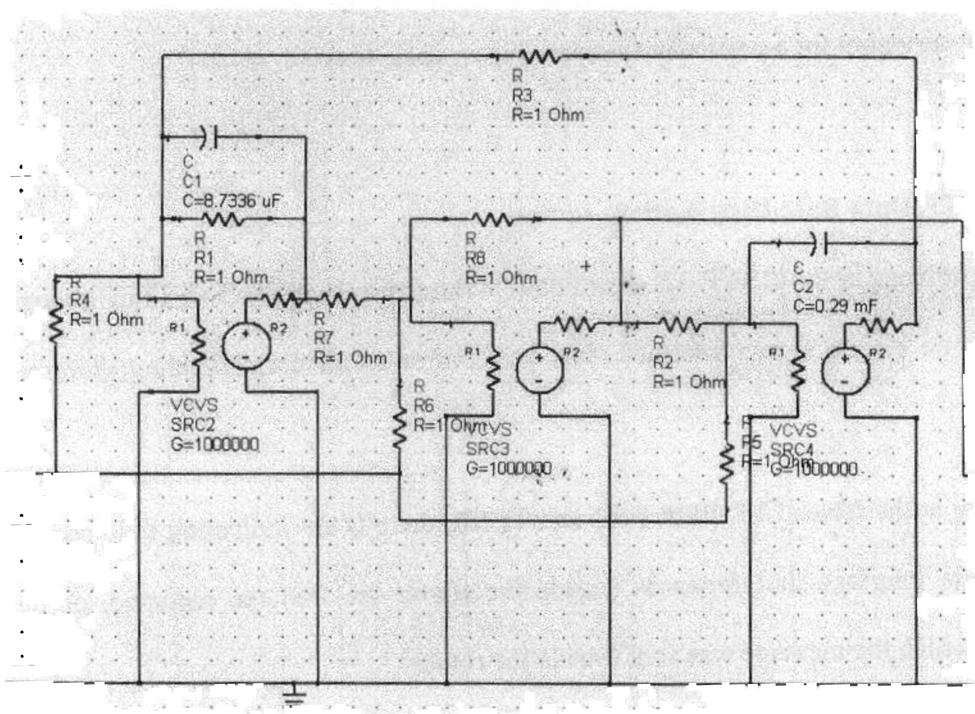

Figure 3: Fleischer-Tow Biquad Filter Stage 1

4.3 Realistic Values Simulation

We will now attempt to magnitude scale the circuit components to be closer to realistic values and then replace the components with realistic circuit component values. These values are listed on the following table:

Table 2: Standard Resistor and Capacitor Values[4]

Standard Resistor Values (±5%)						
1.0	10	100	1.0K	10K	100K	1.0M
1.1	11	110	1.1K	11K	110K	1.1M
1.2	12	120	1.2K	12K	120K	1.2M
1.3	13	130	1.3K	13K	130K	1.3M
1.5	15	150	1.5K	15K	150K	1.5M
1.6	16	160	1.6K	16K	160K	1.6M
1.8	18	180	1.8K	18K	180K	1.8M
2.0	20	200	2.0K	20K	200K	2.0M
2.2	22	220	2.2K	22K	220K	2.2M
2.4	24	240	2.4K	24K	240K	2.4M
2.7	27	270	2.7K	27K	270K	2.7M
3.0	30	300	3.0K	30K	300K	3.0M
3.3	33	330	3.3K	33K	330K	3.3M
3.6	36	360	3.6K	36K	360K	3.6M
3.9	39	390	3.9K	39K	390K	3.9M
4.3	43	430	4.3K	43K	430K	4.3M
4.7	47	470	4.7K	47K	470K	4.7M
5.1	51	510	5.1K	51K	510K	5.1M
5.6	56	560	5.6K	56K	560K	5.6M
6.2	62	620	6.2K	62K	620K	6.2M
6.8	68	680	6.8K	68K	680K	6.8M
7.5	75	750	7.5K	75K	750K	7.5M
8.2	82	820	8.2K	82K	820K	8.2M
9.1	91	910	9.1K	91K	910K	9.1M

Standard Capacitor Values (±10%)						
10pF	100pF	1000pF	.010µF	.10µF	1.0µF	10µF
12pF	120pF	1200pF	.012µF	.12µF	1.2µF	
15pF	150pF	1500pF	.015µF	.15µF	1.5µF	
18pF	180pF	1800pF	.018µF	.18µF	1.8µF	
22pF	220pF	2200pF	.022µF	.22µF	2.2µF	22µF
27pF	270pF	2700pF	.027µF	.27µF	2.7µF	
33pF	330pF	3300pF	.033µF	.33µF	3.3µF	33µF
39pF	390pF	3900pF	.039µF	.39µF	3.9µF	
47pF	470pF	4700pF	.047µF	.47µF	4.7µF	47µF
56pF	560pF	5600pF	.056µF	.56µF	5.6µF	
68pF	680pF	6800pF	.068µF	.68µF	6.8µF	
82pF	820pF	8200pF	.082µF	.82µF	8.2µF	

It should be noted that for realistic component replacement in the remainder of this report this table will be used to obtain values.

We will now proceed to magnitude scale the components in the following way.

We know that:

[4] Website of Dr. Linden McClure, Professor Adjunct, University of Colorado, Standard Resistor and Capacitor Values http://ece-www.colorado.edu/~mcclurel/resistorsandcaps.pdf

components is that the higher cutoff frequency of the stop band has 11.11% error, which is above 10%. Usually it is preferable to keep the error under 10%. It is rather close in this case, and can still be considered a satisfactory filter.

numerical simulation (MATLAB) using realistic component values?

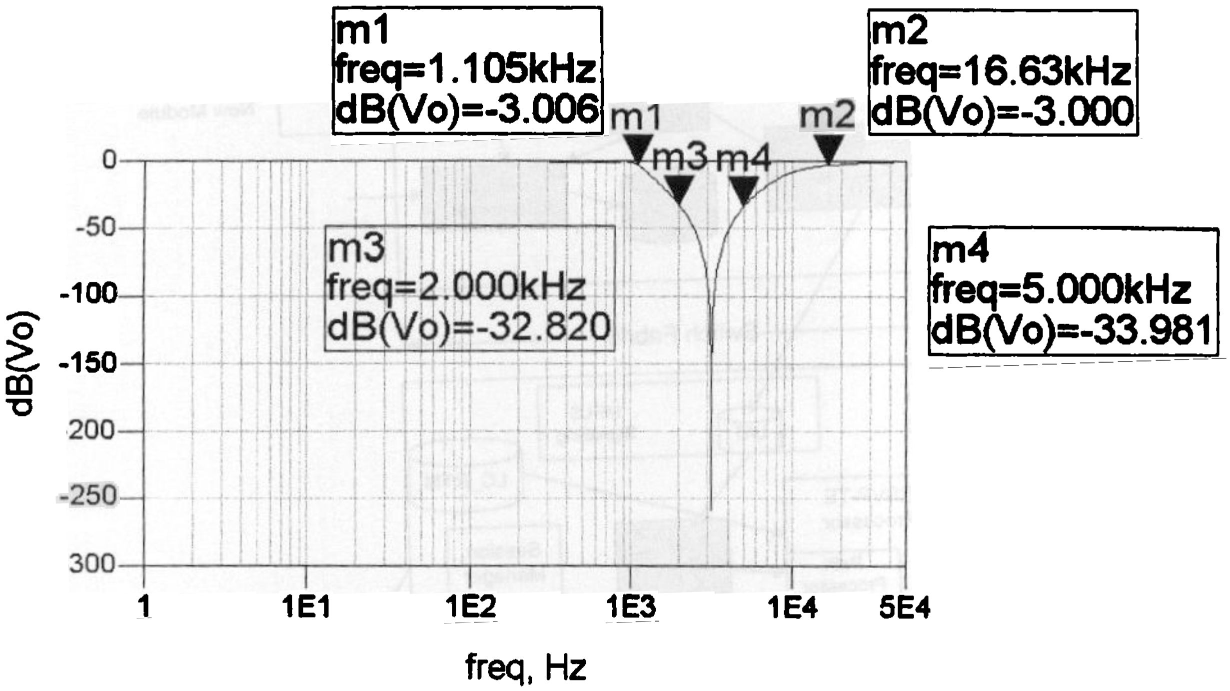

Figure 18: Calculated Value OTA Frequency Response

When analyzing this response we can see that the lower cutoff frequency is very close to the desired 1 kHz. In fact it is at 10% error of the original specification. Seeing as the ideal numerical simulation has a 7.5% error at this frequency we will regard this as a good lower cutoff frequency as it resembles the numerical simulation. The attenuation frequencies of 2 kHz and 5 kHz both satisfy the 30 dB attenuation criteria. The only large discrepancy is the upper cut-off frequency which occurs very late at 16.63 kHz. This is a 66.3% error and is rather unsatisfactory. It is known that when we cascade second order filters to generate filters of order above four, slight errors between the two filters yield a slightly different results than anticipated in the original design. This is perhaps the main reason that the OTA simulation even with ideally calculated values for transconductances used, yields such a poor response. In the case of designing the circuit we reviewed our calculations several times and even attempted to keep all available significant digits, but still the response of this sixth order cascaded OTA filter was still the same as shown above. We can also see that the right side of the frequency response has no ripple, and resembles more of a maximally flat type curve. These curves are known to have a slow rise or fall between pass-band and stop band regions. On the other hand the left side of the response does demonstrate a ripple that is 1 dB in magnitude as desired from the design specifications.

5.3 Realistic Values Simulation

In our software package there were no OTA components only VCCSs as shown in the circuits above when using calculated transconsuctances. For this reason we could not bias the transconductances with bias currents and standard resistor values and were unable to perform standard resistor value simulations. Our capacitors used in the design above were 1 nF which are already a standardized value. It is safe to say however that if this simulation were possible it would yield quite an undesirable response.

You could use - OTA, as you did for your lab

NS

We can now plug in the values that were given for the components above into the general structure shown below:

Show Tm design eqn here

Show sample calculations here

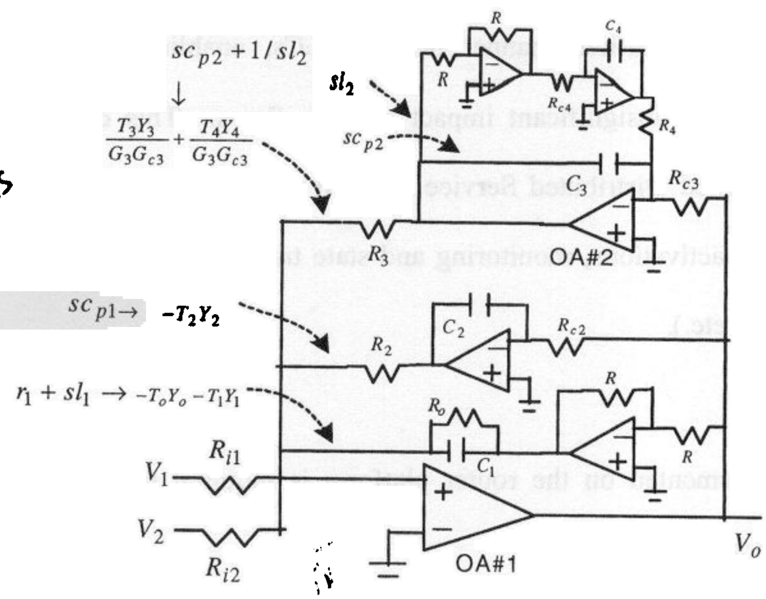

Figure 21: General Structure of a Series Arm in Operational Simulation[7]

Eliminating the unnecessary branches and plugging in the tabulated values we obtain the following structure:

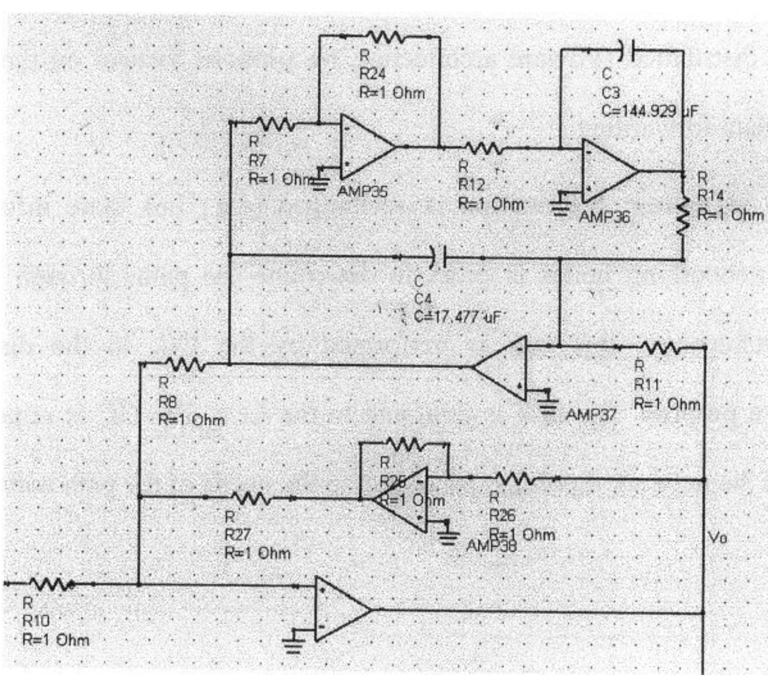

Figure 22: Operational Simulation of Series Arm 3

7. Discussion of Results

As we can see after the derivation of the transfer function there are several ways to implement the desired function. We have gained experience with three different methods during the course of this project. Two of the methods involved splitting the transfer function into 3 second order transfer functions and using standard biquad architectures to simulate each stage. The overall transfer function was then realized by cascading the derived second order architectures. The third architecture used operational simulation principles to simulate each arm of a ladder network to create the desired transfer function directly.

When we compare the two cascaded architectures used, namely Fleischer-Tow active RC circuit, and OTA-C biquad architectures we realized that the active RC circuit performed substantially better. Even with ideal values the OTA circuit did not emulate the numerical response derived in MATLAB. With ideally calculated values the Fleischer-Tow structure performed almost exactly as the numerical simulation did. We then proceeded to replace the components with realistic valued components and still the filter behaved in a satisfactory manner.

It was noted that when cascading more than two second-order filters the response could become undesirable. Apparently the OTA structure is more sensitive to this and performs worse when being cascaded. It has been shown in the class lecture notes that individually implemented active op-amp biquad circuits and OTA biquad circuits both perform well.

Despite some discrepancies we did see that both filters demonstrated attributes that were specified by the design such as the pass-band ripple, as well as the stop band attenuation requirements. If the design requirements are not that strenuous either one of the circuits can be used to implement the desired filter in a cascaded architecture. However in a realistic situation with strenuous requirements we would elect to use the Fleischer-Tow architecture since it performed more precisely even when using rounded off realistic component values.

We can conclude that the OTA structure performed the worst of the three structures in terms of emulating the numerical response generated in MATLAB.

We will now go on to compare the Fleischer-Tow structure with the ladder network response implemented using operational simulation. It can be seen that when using ideally calculated component values the Fleischer-Tow structure has an upper cut-off frequency closer to that of the numerical simulation. All other attributes such as low cutoff frequency, pass-band ripple and stop band attenuation criteria are all satisfied and nearly identical to the numerical simulation from MATLAB. When converting to realistic component values we see that the cutoff frequencies of the operational simulation ladder network actually improve toward specification, while still satisfying all the other design criteria. This is a very interesting result, as it shows that in a realistic situation an operational simulated network experiences the least deviation from component rounding. It does however require the most components to realize and would probably cost the most to implement. This low sensitivity is

8. References

1) R. Schaumann et al, "Design of Analog Filters – Passive, Active RC, and Switched Capacitor", Prentice-Hall Inc., © 1990

2) Rabin Raut Ph.D., ELEC 441 Lecture Note Pack, © Rabin Raut

3) Website of Dr. Linden McClure, Professor Adjunct, University of Colorado, Standard Resistor and Capacitor Values
http://ece-www.colorado.edu/~mcclurel/resistorsandcaps.pdf

4) L.P. Huelsman, "Active and Passive Analog Filter Design – An Introduction", McGraw Hill, Inc., ©1993.