Filter Design on a Budget

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ABSTRACT

A question that repeatedly gets asked is “what values of R and C will give a filter response closest to a given frequency?” This note gives a quick answer to that question. A second question that often is asked “does a lab really need to have a complete stock of 1% resistors in order to implement filters of any frequency?” While there is no single answer that fits every situation or budget, this note gives the most complete answer possible.

1 Introduction

The author recently changed jobs to become a Texas Instruments Application Specialist. One of the first actions taken was to set up a laboratory stock of components. The technician took one look at the list of parts requisitioned and responded with the same response heard from every technician over the years: “Are all of these part values really necessary? Can some be eliminated to get the cost down?” The answer has always been “Yes, it is necessary to be able to implement any filter frequency”. But there has always been a doubt – is that answer really true?

2 A Question of Decades

Not just units of time – but also decades of part values. Passive component values are available in decades, with part values following a logarithmic sequence within each decade. If there is a 1.2-kΩ resistor, for example, 1.2 Ω, 12 Ω, 120 Ω, 12 kΩ, 120 kΩ, 1.2 MΩ, 12 MΩ will also be available. This note can only give general guidance about what decades are needed:

- Filters scale over a fairly wide range. If a resistor is increased by a decade and the capacitor is reduced by a decade, the filter response will remain unchanged. The response of a filter that uses 100 kΩ and 0.1 µF will be the same with 10 kΩ and 1 µF.
- Resistors that are too low will increase power consumption in the circuit, and resistor values that are too high will increase noise.
- High-speed applications use lower values of resistors in the 100 Ω to 1 kΩ range, precision equipment operates best with resistors in the 100 kΩ to 1 MΩ range, while portable equipment uses higher values in the 100 kΩ to 10 MΩ range.
- 1% resistors below 100 Ω and above 10 MΩ are hard to obtain. Precision capacitors below 100 pF and above 0.1 µF are hard to obtain.

A company’s product line and past experience can be used to estimate how many decades are needed. Three decades should be enough. Therefore, any lab procurement will need to include sets of resistors recommended below in three decades for capacitor, and three decades for resistor.

3 The E Sequence of Component Values

Component values follow a logarithmically derived sequence of values, which repeat every decade. The E-values correspond to component tolerance values, which were used to determine the next logarithmic step. For 10% / E-12 components, for example, a component with a value of 1 can be as low as 0.9 or as high as 1.1. The next value in the sequence, with a value of 1.2, can be as low a 1.08 or as high as 1.32. Ideally, there would be no overlap between adjacent values – but there was some arbitrary rounding done originally to simplify the values.

For the E-12 sequence, there are 12 logarithmic steps, likewise 24 for E-24 and 96 for E-96. Values other than these standard values are almost always special order items, with long lead times and added expense.

3.1 E-12 Resistor and Capacitor 10% Values

1.0, 1.2, 1.5, 1.8, 2.2, 2.7, 3.3, 3.9, 4.7, 5.6, 6.8, and 8.2.

3.2 E-24 Resistor and Capacitor 5% Values (Also 1% Capacitors)

1.0, 1.1, 1.2, 1.3, 1.5, 1.6, 1.8, 2.0, 2.2, 2.4, 2.7, 3.0, 3.3, 3.6, 3.9, 4.3, 4.7, 5.1, 5.6, 6.2, 6.8, 7.5, 8.2, and 9.1.

3.3 E-96 Resistor 1% Values

1.00, 1.02, 1.05, 1.07, 1.10, 1.13, 1.15, 1.18, 1.21, 1.24, 1.27, 1.30, 1.33, 1.37, 1.40, 1.43, 1.47, 1.50, 1.54, 1.58, 1.62, 1.65, 1.69, 1.74, 1.78, 1.82, 1.87, 1.91, 1.96, 2.00, 2.05, 2.10, 2.15, 2.21, 2.26, 2.32, 2.37, 2.43, 2.49, 2.55, 2.61, 2.67, 2.74, 2.80, 2.87, 2.94, 3.01, 3.09, 3.16, 3,24, 3.32, 3.40, 3,48, 3.57, 3.65, 3.74, 3.83, 3.92, 4.02, 4.12, 4.22, 4,32, 4.42, 4,53, 4.64, 4.75, 4.87, 4.99, 5.11, 5.23, 5.36, 5.49, 5.62, 5.76, 5.90, 6.04, 6.19, 6.34, 6.49, 6.65, 6.81, 6.98, 7.15, 7.32, 7.50, 7.68, 7.87, 8.06, 8.25, 8.45, 8.66, 8.87, 9.09, 9.31, 9.53, 9.76.

3.4 Other Sequences

Other sequences exist:

- E-192 for 1/2% resistors
- E-6 for 20% resistors and capacitors – now seldom used

These other sequences are not discussed in this note – although designers attempting a three or four pole filter with a single op amp will soon become acquainted with the E-192 series, or even higher precision resistors.

4 Four Filter Precisions

Texas Instruments has recently introduced a spreadsheet that will calculate the optimum values of R and C for a given frequency. This notes uses that tool. Ninety frequency values were selected from 1.0 to 9.9 (corresponding to an arbitrary decade), and the optimum R and C value for each frequency was recorded. This was repeated for four cases:

- E-96 resistors and E-24 capacitors
- E-96 resistors and E-12 capacitors
- E-24 resistors and E-24 capacitors
- E-24 resistors and E-12 capacitors

It should be noted that the author never recommends that 10% capacitors ever be used in filter design, and that critical filter designs often need 1% capacitors. When 10% is selected in the RC calculation spreadsheet, it is understood that the actual capacitors should be 5% tolerance parts, located at E-12 values.

If readers only want a table of optimum passive component values for each frequency, they can stop reading here, and print this application note for the four tables that follow. If the reader wants to procure parts, then the rest of the document will be helpful.

5 What Component Values Need to Be Procured?

Each case above was analyzed to see if all component values were really needed. In every case, certain component values appeared repeatedly, therefore being more important for a well-stocked filter design laboratory. Some good examples are:

- The E-96 value 4.42, which appears for ten frequencies in Table 1.
- The E-96 value 2.21, which appears for eleven frequencies in Table 1.

So far, so good. This accounts for a total of 21 out of 90 frequency combinations, meaning that a substantial reduction in individual part values is possible.

5.1 The E96-E24 Combination

Traditionally, 1% resistors and 5% capacitors have been the default combination of component values for precision filter design. Table 1 shows the optimum component values for 90 values of frequency. As already stated, a lot of component values are repeated. In addition, there are many cases in which two or even three combinations of components produce identical low error values. In these cases, the frequency values are simply repeated in the table for each combination. Some of these frequency combinations are highlighted orange. These are cases that would add to the number of separate E-96 values required. Because there is another way to produce these frequencies, these combinations will receive no more consideration. The remaining E-96 resistor values used to generate all 90 combinations of frequency are listed in a small section on the right side of the table. If all frequency combinations are desired, only 48 out of 96 values or resistor need to be purchased. If 22 out of 90 frequency combinations can be deleted, the number of unique resistor values required goes down to only 23 values, which would be much more economical to procure. The deleted frequencies and resistor values are highlighted in yellow.

5.2 The E96-E12 Combination

Table 2 shows the optimum component values for 90 values of frequency using 1% resistors and 10% capacitor values (the actual tolerance of purchased components should be 5%). Assuming that resistors are relatively economical compared to capacitors, eliminating every other capacitor value would result in substantial cost savings. In addition the capacitor values in between the E-12 values are difficult to obtain. Capacitor manufacturers do not like to supply these values. Applying the same analysis techniques as to the previous table, 59 unique values of 1% resistors are needed to generate all 90 values of frequency. There are 11 more resistor values than in the previous case, but it saves 12 hard to obtain capacitor values. This is a good trade-off. If a lower cost alternative is desired, then 24 unique values of resistor will allow 58 frequencies to be generated. Frequency and resistor values that are deleted are shown in yellow.

Freq	C	R
1.0	3.6	4.42
1.1	3.6	4.02
1.2	1.3	1.00
1.2	3.9	3.40
1.2	3.0	4.42
1.3	3.6	3.40
1.4	3.6	3.16
1.5	2.4	4.42
1.6	3.9	2.55
1.7	3.6	2.61
1.7	2.7	3.48
1.8	6.8	1.30
1.8	2.0	4.42
1.9	1.2	6.98
2.0	3.6	2.21
2.0	1.8	4.42
2.1	2.4	3.16
2.2	1.8	4.02
2.3	1.6	4.32
2.4	5.1	1.30
2.4	3.0	2.21
2.4	1.5	4.42
2.5	9.1	6.98
2.6	2.4	2.55
2.6	1.8	3.40
2.7	1.1	5.36
2.8	4.7	1.21
2.9	1.1	4.99
3.0	2.4	2.21
3.0	1.2	4.42
3.1	3.6	1.43
3.2	2.2	2.26
3.3	1.2	4.02
3.4	3.6	1.30
3.5	9.1	4.99
3.6	2.0	2.21
3.6	1.0	4.42
3.7	5.6	7.68
3.8	8.2	5.11
3.9	1.6	2.55
3.9	1.2	3.40
4.0	3.9	1.02
4.0	1.8	2.21
4.1	4.7	8.25
4.2	4.7	8.06
4.3	2.7	1.37
4.4	1.6	2.26
4.5	1.6	2.21
4.6	8.2	4.22
4.7	2.2	1.54
4.8	1.5	2.21
4.8	7.5	4.42
4.9	9.1	3.57
5.0	2.7	1.18
5.1	2.4	1.30

Freq	C	R
5.2	3.0	1.02
5.2	1.2	2.55
5.3	5.6	5.36
5.4	9.1	3.24
5.5	2.7	1.07
5.6	1.8	1.58
5.6	1.2	2.37
5.7	3.0	9.31
5.8	6.2	4.42
5.9	2.7	1.00
5.9	1.8	1.50
6.0	1.2	2.21
6.1	1.5	1.74
6.1	1.0	2.61
6.1	7.5	3.48
6.2	2.4	1.07
6.3	1.6	1.58
6.4	2.2	1.13
6.4	1.1	2.26
6.5	2.4	1.02
6.6	8.2	2.94
6.7	9.1	2.61
6.8	1.8	1.30
6.9	5.6	4.12
7.0	9.1	2.49
7.1	1.6	1.40
7.2	1.0	2.21
7.3	4.7	4.64
7.4	1.0	2.15
7.5	1.8	1.18
7.6	4.3	4.87
7.7	1.8	1.15
7.8	2.0	1.02
7.9	9.1	2.21
8.0	8.2	2.43
8.1	6.2	3.16
8.2	8.2	2.37
8.3	6.2	3.09
8.4	1.2	1.58
8.5	1.0	1.87
8.6	3.9	4.75
8.7	6.2	2.94
8.8	1.6	1.13
8.9	1.1	1.62
9.0	3.3	5.36
9.1	2.7	6.49
9.2	5.6	3.09
9.3	2.7	6.34
9.4	6.8	2.49
9.4	5.1	3.32
9.5	2.4	6.98
9.6	7.5	2.21
9.7	8.2	2.00
9.8	1.0	1.62
9.9	3.0	5.36

1.00
1.02
1.07
1.13
1.15
1.18
1.21
1.30
1.37
1.40
1.43
1.54
1.58
1.62
1.87
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2.55
2.61
2.94
3.09
3.16
3.24
3.40
3.57
4.02
4.12
4.22
4.32
4.42
4.64
4.75
4.87
4.99
5.11
5.36
6.34
6.49
6.98
7.68
8.06
8.25
9.31

Table 1. E96-E24 Component Values

Freq	C	R
1.0	1.0	1.58
1.1	2.7	5.36
1.2	3.9	3.40
1.3	1.2	1.02
1.4	2.7	4.22
1.5	1.8	5.90
1.6	3.9	
1.7	2.7	3.48
1.8	6.8	1.30
1.9	1.2	6.98
2.0	1.8	4.42
2.1	1.8	4.22
2.2	1.8	4.02
2.3	1.2	5.76
2.4	1.5	
2.5	1.0	6.34
2.6	1.8	3.40
2.7	1.0	5.90
2.8	4.7	1.21
2.9	1.0	5.49
3.0	1.2	4.42
3.1	2.7	1.91
3.2	2.2	
3.3	1.2	4.02
3.4	2.7	1.74
3.4	1.8	2.61
3.5	2.7	1.69
3.6	1.0	4.42
3.7	5.6	7.68
3.8	8.2	5.11
3.9	1.2	
4.0	3.9	1.02
4.0	1.8	2.21
4.1	4.7	8.25
4.2	4.7	8.06
4.3	2.7	1.37
4.4	1.2	3.01
4.5	8.2	4.32
4.6	8.2	
4.7	2.2	1.54
4.8	1.5	2.21
4.9	1.0	3.24
5.0	2.7	1.18
5.1	4.7	6.65
5.2	1.2	2.55
5.3	5.6	5.36
5.4	1.0	
5.5	2.7	1.07

Freq	C	R
5.6	1.8	1.58
5.6	1.2	2.37
5.7	2.2	1.27
5.8	1.0	2.74
5.9	2.7	1.00
5.9	1.8	1.5
6.0	1.2	
6.1	1.5	1.74
6.1	1	2.61
6.2	2.7	9.53
6.3	2.2	1.15
6.4	2.2	1.13
6.5	2.7	9.09
6.6	8.2	2.94
6.7	1.5	
6.7	1	2.37
6.8	1.8	1.30
6.9	5.6	4.12
7.0	2.7	8.45
7.1	1.2	1.87
7.2	1.0	2.21
7.3	4.7	4.64
7.4	1.0	
7.5	1.8	1.18
7.6	5.6	3.74
7.7	1.8	1.15
7.8	3.9	5.23
7.9	2.7	7.50
8.0	8.2	2.43
8.1	2.7	7.32
8.2	8.2	
8.3	1.0	1.91
8.4	1.2	1.58
8.5	1.0	1.87
8.6	3.9	4.75
8.7	1.8	1.02
8.8	3.9	4.64
8.9	2.7	6.65
9.0	3.3	
9.1	2.7	6.49
9.2	5.6	3.09
9.3	2.7	6.34
9.4	6.8	2.49
9.5	1.8	9.31
9.6	6.8	2.43
9.7	8.2	2.00
9.8	1.0	
9.9	5.6	2.87

1.00	3.40
1.02	3.48
1.07	3.74
1.13	4.02
1.15	4.12
1.18	4.22
1.21	4.32
1.27	
1.30	4.64
1.37	4.75
1.54	5.11
1.58	5.23
1.62	5.36
1.69	5.49
1.74	5.76
1.87	
1.91	6.34
2.00	6.49
2.15	6.65
2.21	6.98
2.26	7.32
2.43	7.50
2.49	7.68
2.55	
2.74	8.25
2.87	8.45
2.94	9.09
3.01	9.31
3.09	9.53
3.24	

Table 2. E96-E12 Component Values

5.3 The E24-E24 and E24-E12 Combinations

The same analysis techniques were applied to the E24-E24 and E24-E12 cases in Table 3. In these cases, there is very little motivation for reducing the number of resistor values, as good resistor kits containing these values are relatively inexpensive. Combinations pair, because the resistor and capacitor values can interchange.

There is very little advantage to purchasing all E24 capacitor values, because all but 16 frequencies can be produced optimally with E12 capacitor values. In addition, close examination reveals that two or three frequencies are produced by the same combination. This is because the combinations are only accurate to 2 1/2% in some cases, causing overlap. There are really only 12 discrete frequencies produced by seven additional capacitor values. Therefore, only 19 values of capacitance and 24 of resistance are needed per decade.

The designer is cautioned that 5% components are only useable for low order (one or two pole) lowpass and highpass filters. Precision bandpass and notch filter design with anything but 1% resistors and capacitors is usually disastrous. Figure 1 shows a notch filter implemented with different tolerances of passive components. The response with perfect components is shown in green for each combination. Deep notches at other frequencies may, or may not have occurred in the random worst case examples – but the primary issue is the worst-case notch depth. With 1% resistors and 1% capacitors, the very worst-case notch depth is about 18 dB. This is almost a 10:1 reduction – well worth the effort of implementing the notch – especially since the worst case is a statistical anomaly and typical performance is much better.

The situation deteriorates rapidly with 1% resistors and 5% capacitors. The simulation program was not looking for deep notches and did not randomly find any. The notch depth at the center frequency can only be assured to be 6 dB, which is only a 2:1 rejection.

When 5% resistors and 5% capacitors are used, one of the worst-case examples hardly found a notch at all, which means there is no assurance that the notch filter will operate at all.

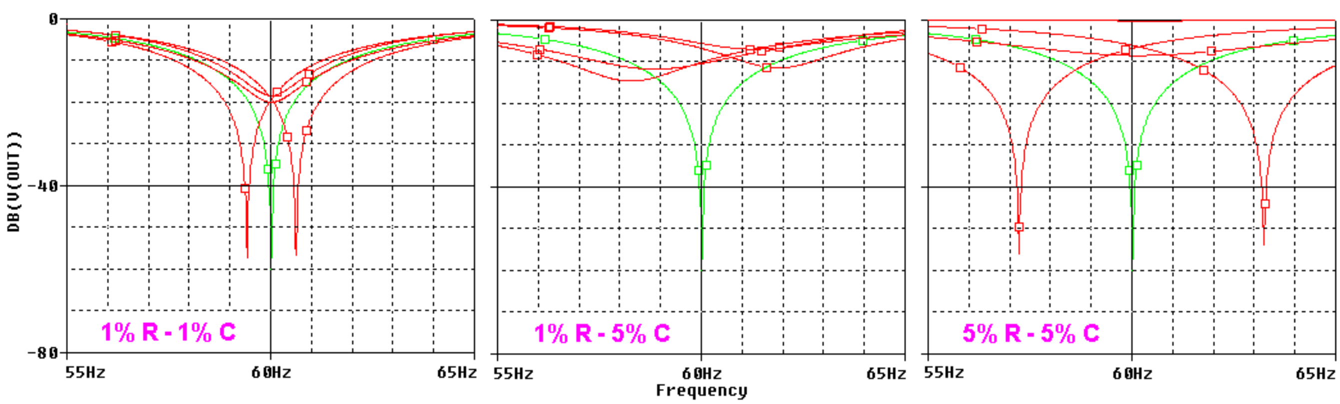

Figure 1. Notch Filter Design With Different Tolerance Components.

Freq	Set 1 C	Set 1 R	Set 2 C	Set 2 R	Set 3 C	Set 3 R	Set 4 C	Set 4 R
	1.2							
1.1	1.2	1.2						
1.2	1.2	1.1						
1.3	6.8	1.8	1.8	6.8				
1.4	4.7	2.4						
1.5	8.2	1.3						
1.6	6.2	1.6	1.6	6.2	3.3	3.0		
1.7	3.9	2.4						
	6.8							
1.9	1.5	5.6						
2.0	3.3	2.4	2.2	3.6				
2.1	4.7	1.6						
2.2	3.3	2.2	2.2	3.3				
2.3	4.3	1.6	1.6	4.3	3.9	1.8	1.8	3.9
2.4	5.1	1.3	1.3	5.1	3.3	2.0	2.2	3.0
2.5	1.5	4.3						
	1.2							
2.7	3.9	1.5	1.5	3.9				
2.8	9.1	6.2	6.2	9.1	4.7	1.2	1.2	4.7
2.9	8.2	6.8	6.8	8.2				
3.0	3.3	1.6	2.2	2.4				
3.1	1.2	4.3						
3.2	3.3	1.5	1.5	3.3				
3.3	2.2	2.2						
3.4	3.9	1.2	1.2	3.9				
3.5	8.2	5.6	5.6	8.2				
3.6	2.2	2.0						
3.7	1.0	4.3						
3.8	8.2	5.1						
	2.7		1.5					
4.0	3.3	1.2	2.2	1.8	1.8	2.2		
4.1	3.9	1.0						
4.2	6.8	5.6						
4.3	3.3	1.1						
4.4	3.3	1.1						
4.5	8.2	4.3						
4.6	6.8	5.1						
	6.8							
4.8	1.5	2.2						
4.9	2.7	1.2	1.8	1.8	1.2	2.7		
5.0	6.8	4.7	4.7	6.8				
5.1	2.4	1.3	1.3	2.4	5.6	5.6		
5.2	2.4	1.3	1.3	2.4	3.3	9.1		
5.3	3.3	9.1						
5.4	8.2	3.6						

	Set 1		Set 2		Set 3		Set 4		Set 5	
	C	R	C	R	C		C		C	R
5.5	1.8	1.6								
5.6	5.6	5.1								
5.7	5.6	5.1								
5.8	9.1	3.0	3.0	9.1	8.2	3.3	3.3	8.2		
5.9	2.7	1.0	1.8	1.5	1.5	1.8	1.0	2.7		
6.0	6.8	3.9	3.9	6.8						
6.1	4.7	5.6								
	1.6	1.6	4.7	5.6						
6.3	1.6	1.6	3.3	7.5						
6.4	3.3	7.5								
6.5	6.8	3.6								
6.6	5.6	4.3								
6.7	4.7	5.1								
6.8	1.8	1.3								
6.9	1.8	1.3								
	3.0	7.5	7.5	3.0	1.5					
7.1	6.8	3.3	3.3	6.8						
7.2	4.7	4.7								
7.3	3.9	5.6	5.6	3.3						
7.4	1.8	1.2	1.2	1.8						
7.5	1.8	1.2	1.2	1.8						
7.6	1.6	1.3	1.3	1.6	3.3	6.2				
7.7	1.6	1.3	1.3	1.6	3.3	6.2				
	6.8	3.0								
7.9	5.6	3.6								
8.0	3.9	5.1								
8.1	8.2	2.4								
8.2	1.5	1.3								
8.3	1.2	1.6								
8.4	1.2	1.6								
8.5	6.2	3.0	3.0	6.2	5.6	3.3	3.3	5.6		
	4.3	4.3	5.6	3.3	3.3					
8.7	4.7	3.9	3.9	4.7						
8.8	8.2	2.2	2.2	8.2						
8.9	7.5	2.4	2.4	7.5	1.8	1.0	1.5	1.2	1.2	1.5
9.0	1.6	1.1	1.1	1.6	1.8	1.0	1.5	1.2	1.2	1.5
9.1	1.6	1.1	1.1	1.6	1.8	1.0	1.5	1.2	1.2	1.5
9.2	1.6	1.1	1.1	1.6	4.7	3.6				
9.3	4.7	3.6								
	4.7	3.6								
9.5	2.7	6.2								
9.6	1.5	1.1								
9.7	8.2	2.0								
9.8	6.8	2.4								
9.9	1.0	1.6								

Table 3. E24 Combinations

6 Conclusion

The decision about which components to purchase to cover the needs of a filter design lab ultimately involves a tradeoff between budget and the need to design all combination of frequency. There are some absolutes, however, such as the need to procure 1% resistors if accurate frequency response is needed, and the need to purchase 1% capacitors if high Q notch or bandpass filters are to be designed.

IMPORTANT NOTICE

Mailing Address:

Texas Instruments
Post Office Box 655303
Dallas, Texas 75265