Choosing Resistors and Capacitors for Op-Amp Active Filters

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The designer's dilemma: Justification for a personal choice

After all analysis and calculations have been performed, design ultimately requires that the designer makes an intelligent choice of a component value. Typically, the result of a design is component ratios rather than absolute values. In some cases there is only a single specific value and we do not have a choice. Those situations are the easy ones and this paper is not applicable. But when you have component ratios then this paper will guide you through the logic of choosing practical component values. Since an equation does not exist for this process, then how does the designer justify the choice made? The solution set to a design is generally infinite and any choice made can be shown to mathematically work perfectly even if in practice the choice is unworkable. Thus, in practice, the solution set is less than infinite. The question is, can we establish a practical bounds on the solution set so that any choice made within those bounds works both mathematically and in practice? The answer is yes. The process is empirical rather than mathematical and involves human opinions. The end result is a mathematics that gives reasonable bounds to stay within. Since we are going to strive to stay well within the bounds there is no point in attempting to compute the bounds with high precision. Our goal is to determine the rough center of a good zone to be in and we will make our choices about that zone.

Concept Illustration

Let me illustrate the concept of establishing bounds by way of an example. The goal is to construct a simple RC circuit with a time constant of 1 second. There are an infinite number of resistor and capacitor values whose product is one second. One possibility is to use a resistance of 0.001 Ohms and a capacitance of 1000 Farads. Another possibility is to use a resistance of $1x10^{12}$ Ohms and a capacitance of 1 picofarad. Both of these examples are mathematically correct but extremely impractical. In one case the resistance seems to be too small and in the other case the resistance seems to be too large.

The good news is that if one can identify values that are too small and that are too large then it is possible to determine medium values that are just-right. The medium value is the center of a good zone of values to use. We will define the medium or just-right value as the geometric mean (i.e. square root of the product) of the largest value deemed to be too small and the smallest value deemed to be too large. The designer may then shift the value towards one extreme or the other depending on other tradeoffs or considerations.

Consider the issue of determining the largest too small value for the resistor. Clearly, 0.001 Ohms was way too small. So let's try a factor of 1000 larger or 1 Ohm. This is an improvement but still requires a 1 Farad capacitor and besides, 1 Ohm is not large compared to inherent wiring resistance. So let's try a factor of 1000 larger or 1000

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Ohms. This value requires only a 1000 microfarad capacitor and seems to be acceptable. We are not looking for acceptable values right now – the goal is to find where discomfort starts. So, let's back off a factor of 10 and try 100 Ohms. This requires a 10,000 microfarad capacitor which is rather large. Some people might consider 100 Ohms too small. Others may feel comfortable down to 10 Ohms. To bring this part of the quest to an end, let us declare that 100 Ohms is the largest value that we can determine that is too small.

Now consider the issue of determining the smallest too large value for the resistor. Going down a factor of 1000 from the original example results in a resistor of $1\text{x}10^9$ Ohms which requires a 0.001 microfarad capacitor. If we go down by another factor of 1000 we have $1\text{x}10^6$ Ohms which requires a 1 microfarad capacitor. This seems acceptable – but that is not our goal at the moment. So let us increase the resistor by a factor of 10. Now we have $10\text{x}10^6$ Ohms and 0.1 microfarads. There is still room for the resistor to become larger so let's increase it by another factor of 10. Now we have $100\text{x}10^6$ Ohms and 0.01 microfarads. This is definitely at an uncomfortable extreme. Let us declare that 100 MΩ is the smallest too large value.

The geometric mean of 100 Ohms and 100 MΩ is 100 kΩ. So, the just-right solution is 100 kΩ and 10 microfarads. Note that there is a wide range of acceptable values. Anything from about 1000 Ohms to 10 MΩ should give us good results. Depending on other criteria, we might want to use a larger or smaller value than 100 kΩ. The important thing we have done is to establish practical limits to the infinite solution set. So we have our geometric mean value of 100 kΩ but we choose a value up or down of over an order of magnitude and still be in the "good zone."

A Mathematical Solution

We do not want to go through the preceding exercise for every component in our design. The good news is that there is a general solution to the problem customized for op-amp RC circuits. The solution is based on the fact that external impedances in an op-amp circuit generally should be larger than about 1000 Ohms (limited by maximum linear source and sink currents) and less than about 10 MΩ (with high impedances, parasitic conductances and capacitance can significantly alter desired circuit performance). Also, op-amp RC filter circuits are generally constructed in the 0.1 Hz to 100 kHz range. It is also desirable to keep capacitances under about 1 microfarad so that quality film type capacitors can be used (avoid using electrolytic capacitors in filter circuits). This information lets us develop a mathematical criteria for choosing component values.

The result is a set of equations that define practical median values for resistors and capacitors. These equations have been derived based on the experience and opinions of the author and have been coerced into fitting the preceding criteria. At frequencies in the 100 kHz range, signal amplitudes tend to be small thus permitting impedances smaller than 1000 Ohms.

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$R_{median} = 4 \times 10^5$ / sqrt(frequency)   Eq. 1

$C_{median} = 4 \times 10^{-7}$ / sqrt(frequency)   Eq. 2

Or, when a specific time constant is involved, the above equations can be written as:

$R_{median} = 1 \times 10^6$ * sqrt(time constant)   Eq. 3

$C_{median} = 1 \times 10^{-6}$ * sqrt(time constant)   Eq. 4

where
> **R_{median}** is in Ohms
> **C_{median}** is in Farads
> **frequency** is in Hz and is either the cutoff, peak, or notch frequency of the filter
> **time constant** is in seconds

The author recommends that the actual value chosen be within about one-fifth to five times the median value calculated. These limits can be exceeded as needed provided the consequences of high or low impedances are understood and dealt with appropriately.

In second-order op-amp active filter circuits there are generally two resistors and two capacitors. Since only a limited set of actual capacitor values is available, the capacitors should always be determined first. Sometimes the capacitor values can be equal to each other and selected to be a standard value. Sometimes the capacitor values must differ by a chosen ratio – the ratio chosen conveniently to exactly use standard available values. When the capacitor values differ by a set ratio, then the best overall solution is for the calculated C_{median} to be the geometric mean of the two capacitor values. This is achieved by first calculating C_{median} using Equation 4. Then, multiply C_{median} by the square-root of the target capacitance ratio (use the reciprocal as necessary for a greater than 1.00 result). Round this capacitance to a standard capacitance value. Then divide the rounded value by the target capacitance ratio and round that result to a standard capacitance value. The actual ratio of capacitances will probably be somewhat different than the original target but that does not matter as the calculations for the resistance take this into account and produce the required result.

Once the capacitor values are chosen then the resistor values calculate to specific values – no choice is needed nor possible. It should be noted that these specific resistor values will generally be within the author's recommended bounds provided that the geometric mean of the two capacitor values is C_{median}. The geometric mean of the two resistors will then generally be similar to R_{median}. Exceptions may occur when the Q of the circuit is higher than about 5 as component ratios can become large. That may require that you go back and shift the original median calculation towards one of the recommended extremes. Design is typically an iterative process.

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In closing, I hope that all readers were attentive enough to notice that the just-right set of values for a 1 second time constant were determined to be 100 kΩ and 10 microfarads and that Equations 3 and 4 suggest the median values to be 1 MΩ and 1 microfarad. The difference is due to the additional constraints imposed by the author on the solution set for use specifically in op-amp filter circuits. It also means that there is not a precise answer. Still, either solution is good.

The following table summarizes the range of values to use based on the cut-off, peak, or notch frequency of interest. Note the inverse square-root of frequency relationship.

Frequency	Rmin	Rmed	Rmax		Cmin	Cmed	Cmax	
0.1 Hz	250k	1.3M	6.3M	Ohms	250n	1.3u	6.3u	Farads
1	80k	400k	2M		80n	400n	2u	
10	25k	130k	630k		25n	130n	630n	
100	8k	40k	200k		8n	40n	200n	
1,000	2.5k	13k	63k		2.5n	13n	63n	
10,000	800	4k	20k		800p	4n	20n	
100,000	250	1.3k	6.3k		250p	1.3n	6.3n	

Table 1: Good values to use for the specified frequency range

The concepts in Table 1 can be extended to frequencies in the range of about an order of magnitude higher or lower. Beyond that, this table may be less than optimum and should be adjusted as needed. Never use this table as a substitute for thinking and understanding.