

Using the Texas Instruments Filter Design Database

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ABSTRACT

Texas Instruments applications personnel have decades of collective experience designing active filters using operational amplifiers (op-amps). This information has been made available interactively through the Texas Instruments KnowledgeBase system. Although not every filter design topic can be covered in the KnowledgeBase format, a very large percentage of filter design problems have been addressed. This application note is a user's guide for this information, telling the designer how to access and use the information.

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1 Introduction

From the TI web page:

The Semiconductor Technical Support Analog Products KnowledgeBase is an interactive, on-line system for helping you resolve your problem over the Internet. You use your Web browser to interact with the Analog Products KnowledgeBase by describing your problem and answering *questions* that help the Analog Products KnowledgeBase guide you to the solution you need. The Analog Products KnowledgeBase searches its repository of known solutions (the KnowledgeBase) and presents you with the solutions that are most likely to solve your problem. Working with the Analog Products KnowledgeBase is an interactive process. Every time you refine the description of your problem or answer questions, click the *Next* button. The Analog Products KnowledgeBase displays a new page with new recommendations. Continue to interact with the Analog Products KnowledgeBase until you find the solution to your problem. If you cannot find a solution, click the E-mail Technical Support button to request direct support.

The KnowledgeBase is used as the home of the TI Filter Design Database. If a designer has a specific design question about a particular filter, they can always access the solution directly. The filter design database, however, has a top-level structure to aid designers at every experience level.

2 Accessing the Filter Design Data Base

The TI Filter Design Database is accessed through the KnowledgeBase link on the Texas Instruments Home page. Click on the KnowledgeBase button:

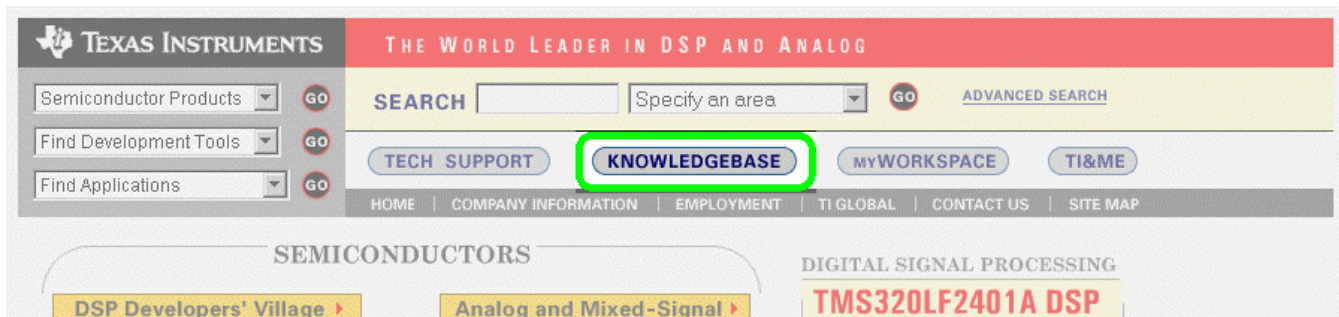


Figure 1. KnowledgeBase Button on TI Home Page

Three KnowledgeBase options are presented:

- The DSP KnowledgeBase
- The Analog & Mixed-Signal KnowledgeBase
- The Digital Logic Products KnowledgeBase

Select the Analog & Mixed-Signal KnowledgeBase by clicking on it.

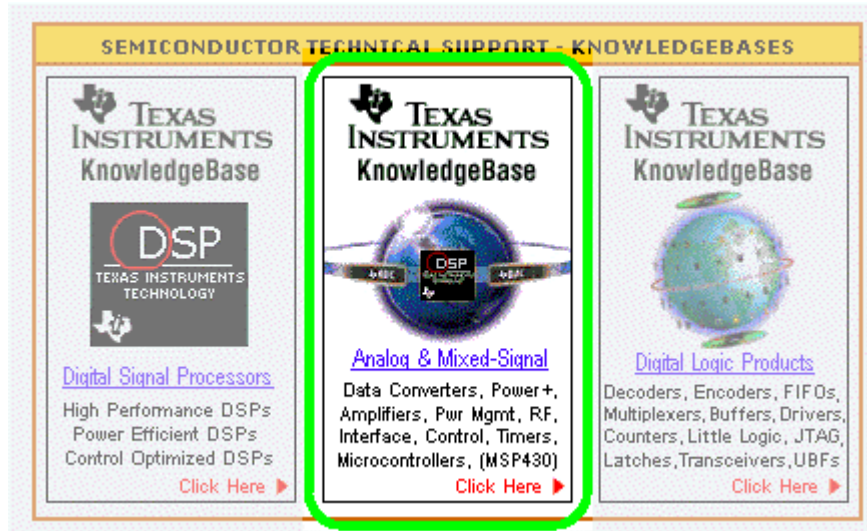


Figure 2. Analog and Mixed Signal Area of TI KnowledgeBase

The designer is presented with a plain English search box, with other blanks that narrow the focus of the search. The Filter Design Tool is available in the *Frequently Searched Topics* category near the bottom.

Check the box by clicking on it, and then click on the View button:

Welcome to the TI Analog & Mixed-Signal Products Technical Support KnowledgeBase. You may either "Ask a Question" in the search box or select an item from our Frequently Searched Topics section. If you can't find what you are looking for? [Click here.](#)

You may perform a SEARCH by "Asking a Question" or entering "Keywords" in the box below:

Use the * (wildcard) for partial device names or alone to view all solutions.

Search "Natural Language"; i.e.: What is Op Amp Slew Rate? ([Search Tips](#))

Search "Boolean Keywords"; i.e.: Op Amp AND Slew <NEAR/3> Rate ([Search Tips](#))

Clarifying Questions
Answering these questions may help "focus" your search.

What type of Analog/Mixed Signal product are you using?

What type of Document would you like to search?

Frequently Searched Topics

For more information on one or more of these topics, please make your selection from the list below.

Op Amp Filter Design Tool

Op Amp Specifications

MSP430 Design

1394

Interfacing Data Converters to DSP's

DSP Power-Vcore, Vio, Sequencing

High Efficiency Battery Power Converters

Battery Management-Charging, Gas Gauge, Lilon Protection

Phase Shifted Full Bridge for High Power

How to use the PowerPAD package

Military Qualified

Figure 3. Frequently Searched Topics Portion of Analog and Mixed Signal Database

Designers are then presented with Search Returns. Select Analog Filter Op-amp Design from the list.

Search Returns
Select the most relevant solution from the list for more info

- [1. Analog Filter Wizard](#)
- [2. Analog Filter Expert](#)
- [3. Analog Filter Op-amp Design](#)
- [4. Current Feedback Analog Filter Expert](#)
- [5. Filter Design Wizard - Low Pass Filters](#)
- [6. Filter Wizard - 2 Pole High Pass Filter](#)

Figure 4. Analog Filter Op-Amp Design Selection

At this point, the top levels of the Analog Filter Design Database are displayed.

3 **Analog Filter Op-Amp Design**

The top level Filter Design item asks designers to select their own level of expertise—what type of advice they want. A large number of people access the KnowledgeBase, from teenage home hobbyists with very little experience to doctorate-degreed professors seeking advice on very advanced nuances of filter design. Four broad categories of support are offered:

- What type of filter do I need? - a guide for beginners.
- The Filter Wizard, for less experienced designers.
- The Filter Expert, for more experienced designers.
- Phone support. Texas Instruments receives many inquiries that are beyond a simple question and answer format. These inquiries should be directed to an applications engineer, who has extensive experience. Advanced topics include:
 - Component ratios for exact ripple values in Chebyshev filters.
 - Inverse (reverse) Chebyshev and Elliptic filter characteristics.
 - Filter orders greater than 2.
 - Multiple stages all pass filters.
 - Filters optimized for group delay.
 - High-speed analog filtering.

3.1 **Analog Filter Op-Amp Design**

This tutorial walks designers through the basic concepts and guides them to the correct type of filter for their application. The tutorial offers help for designers who have a signal they want to pass, and signals they wish to reject, but have no idea what filter they really need, or maybe even what it is called. It is also aimed at teenage hobbyists, who hopefully will be encouraged to give it a try, and someday enter the profession as a competent analog designer in their own right.

The questions asked, in order, are:

- What frequencies are wanted, and what frequencies are not wanted?
- How much rejection is needed on the frequencies that are not wanted?
- Which is important: amplitude, phase, delay, or some combination of these?
- Is cost more important, or is the ability to make changes?
- What power supplies are available?
- How do I select R's and C's for a Filter Circuit?

Designers proceed sequentially through all of the questions. At the end of this process, they will be able to precisely specify what they need. Designers can then go on to the Filter Wizard for the design directly, or to the Filter Expert if they know a little bit more than average on the topic.

The last question - *How do I select R's and C's for a Filter Circuit?* - brings up a spreadsheet. Section 5 of this application report is a user guide for the spreadsheet.

3.2 Filter Wizard Analog

The Filter Wizard gives solutions that offer the best compromise of performance and low component count for single supply, voltage feedback operational amplifier filter design. These design solutions should satisfy 90% of filter design needs. The Wizard is aimed at the designer who has a job to do, and needs to have an answer quickly. It will produce a good filter, although maybe not the best filter for the application. The Filter Wizard assumes that a designer is using single-ended voltage feedback amplifiers that operate off a single power supply. If that is not the case, the designer is warned to use the Filter Expert. Experienced designers may be tempted to go to the Wizard for an answer, but a couple of extra steps will allow them to get an even better answer from the Filter Expert.

The Filter Wizard leads the designers to a small subset of the designs available on the database—those designs most likely to meet designers' needs. It does this by quickly narrowing the designer's search to a particular type of filter, and then asking one or two questions at most to characterize that filter further.

The designer is asked:

- What frequency (or frequency range) needs to be rejected, and what frequency (or frequency range) needs to be passed?

All filter designs must have a center or corner frequency. This is a fundamental design point for the system. Center frequencies for bandpass, notch, and band reject frequencies are straightforward, except they are a logarithmic center, not a linear center frequency. Corner frequencies are defined for low pass and high pass filters. In most cases, they are at, or close to, the upper end of the bandwidth the designer is interested in. In the case of Bessel filters, however, the corner frequency may be moved to include harmonics of the fundamental frequency.

The next set of questions characterizes the type of filter the designer needs:

- Do low frequencies need to be passed and high frequencies rejected? Designers need to implement a Low Pass Filter.
- Do high frequencies need to be passed and low frequencies rejected? Designers need to implement a High Pass Filter.
- Does only a single frequency (or narrow frequency range) need to be passed? Designers need to implement a Bandpass Filter. Otherwise:
- Does a wide frequency range need to be passed with rejection above and below the range? Designers should implement a High Pass Filter, cascaded with a Low Pass Filter.

- Does only a single frequency (or narrow frequency range) need to be rejected? Designers need to implement a Notch Filter.

Designers follow links to the final circuit design (or goes there directly). The emphasis here is on low cost solutions, but there are a couple of exceptions. The wizard chooses the more difficult single-supply architecture, because it is more commonly used. Notch and Bandpass filters are notoriously troublesome, so the wizard opts for more complex solutions that are more likely to work the first time and be less temperamental.

3.3 Analog Filter Expert

The Filter Expert gives a comprehensive set of design solutions for critical applications that demand tighter filter performance. Filter options such as split (dual) supplies, fully differential op amp filters, and current feedback filters are supported, as are Bessel and Chebyshev response curves. Options that are deemed impractical - leading to unreasonable resistance values, large numbers of op amps for a simple function, etc. are not supported. The filter expert does not support every topology available, because there is no compelling reason to do so. Those presented cover just about all eventualities. The best that can be obtained with another filter topology would be parity with something presented in the KnowledgeBase. Designers are assumed to have the power to make judgment calls on design trade-offs, which are so much a part analog design. These trade-offs primarily are things like:

- The amount of roll-off required by the filter versus things like the phase and delay response.
- The number of op-amps used by the filter versus the control one has over the characteristics of the filter.
- When designers enter the Filter Expert, they are presented with four options:
 - Filter designs that operate off of single power supplies.
 - Filter designs that operate off of split (dual) power supplies.
 - Filter designs that utilize current feedback op amps.
 - Filter designs that utilize fully differential op amps.

This represents a compromise as well. Single supply current feedback and differential op amp circuits are not discussed.

Current feedback amplifiers are not optimized for single supply operation, although there is no technical reason why they cannot be used with a single supply. If the designer is interested in that mode of operation, they should start with the current feedback option to learn what configurations are available, and then look at that configuration in the single supply expert to see how the schematic must be modified for single supply operation.

Fully Differential op amps can also be used in a single supply mode. The designer is cautioned that the V_{OCM} input, although it can be used to provide a virtual ground (half supply) reference, may have to be connected to the A/D converter V_{ref} output for maximum converter accuracy. It is probably best to contact Texas Instruments Applications for fully differential op amp filter circuits that must be operated from a single power supply.

When the designer selects one of the options, they are taken to a filter design wizard for that type of amplifier. Central to that wizard will be a graphic that looks like this:

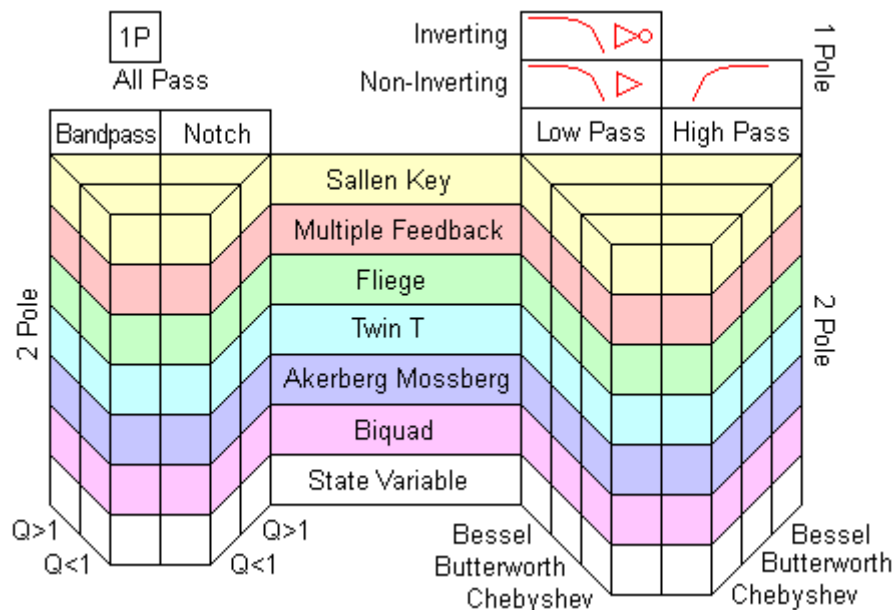


Figure 5. Example of Filter Design Image Map

This picture, when it appears on the web, is a clickable image map. It is not clickable in this document, of course. Web users should be familiar with image maps by now, but for those who are not – most words and shapes on the graphic contains a hyperlink to a different KnowledgeBase filter item. Designers move the mouse across the graphic to different items, and then click on the one of interest.

Designers will notice that the image map has a pseudo-3D appearance. This was done so that all combinations of three independent concepts could be presented. For example, the Sallen Key 2 pole filter topology is presented on the top row of the 3D portion. As a guide for designers, everything related to Sallen Key filters is colored yellow. As designers move the mouse to the center, over the words Sallen Key, a general description of this topology is presented.

Moving to the immediate left moves into the high Q implementation of the topology. Moving further to the left and slightly down moves into the low Q implementation of the topology. For all low Q notch and low Q bandpass filters, designers are presented with an alternative that will provide superior performance. If designers insist on doing the low Q filter with a single op amp, the KnowledgeBase format is inadequate to describe all that must be done to filter components. Designers need to contact Texas Instruments applications.

Moving to the right of the Sallen Key general description link, designers are presented with low pass and high pass filter options. As the mouse is moved through the first three boxes (right and slightly down, low pass options are presented from Bessel through Butterworth to Chebyshev. These filter types present a type of continuum ranging from:

- Slower rates of amplitude roll-off to faster roll-off.
- Less severe rates of phase change to more severe phase change.
- Flat delay times to more and more delay near the corner frequency.

Moving further right and slightly up, designers are presented with the high pass options from Chebyshev to Bessel (reversed from the low pass options).

Looking down each column, the only thing that changes is the filter topology. The ones near the top have less op amps and are more difficult to calculate and change, the ones further down have more op amps and are easier to calculate and change.

4 A Design Example

When designers click on a knowledgebase item, a filter schematic will appear, with any design notes that are needed to support the design. The schematics appear reduced 50%; designers can click on the schematic (or any figure in the knowledgebase) to expand it to 100%. The following example is for a split supply 2 pole Multiple Feedback (MFB) high pass filter:

Bessel

$$F_o = 1 / (2\pi RC)$$

$$R1 = 0.73R$$

$$R2 = 2.19R$$

$$C1 = C2 = C3 = C$$

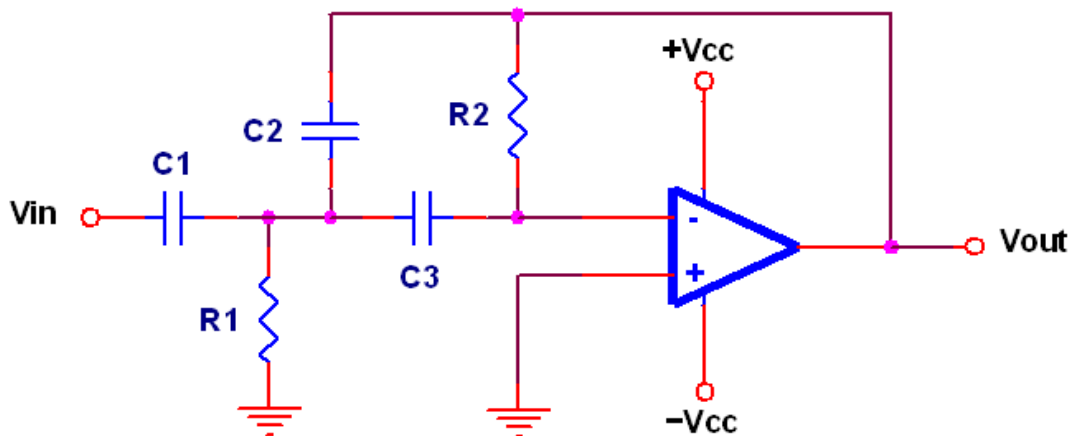


Figure 6. Example of Filter Design Item

To complete the design:

- Designers must know the corner frequency, for example 1 MHz.
- Designers then select a value of capacitor, for example 100 pF.

At this point, all resistor values can now be calculated. Solving the first equation for “R”:

$$\frac{1}{2\pi CF_o} = R$$

$$\frac{1}{2 \cdot \pi \cdot 100 \times 10^{-12} \cdot 1 \times 10^6} = 1591.5 \Omega$$

This is a *raw* value of resistance. For some filters, it can be used directly. For this filter example, however, some correction factors for the resistors are used. Designers take the raw value of the resistor and apply the correction factor, then pick the closest standard resistor value.

- $R1 = 1591.5 \times 0.73 = 1161.8 \Omega$, the designer picks 1.15 kΩ.
- $R1 = 1591.5 \times 2.19 = 3485.5 \Omega$, the designer picks 3.48 kΩ.

Simulations show that the results are correct for a 1 MHz, unity gain Bessel High Pass filter:

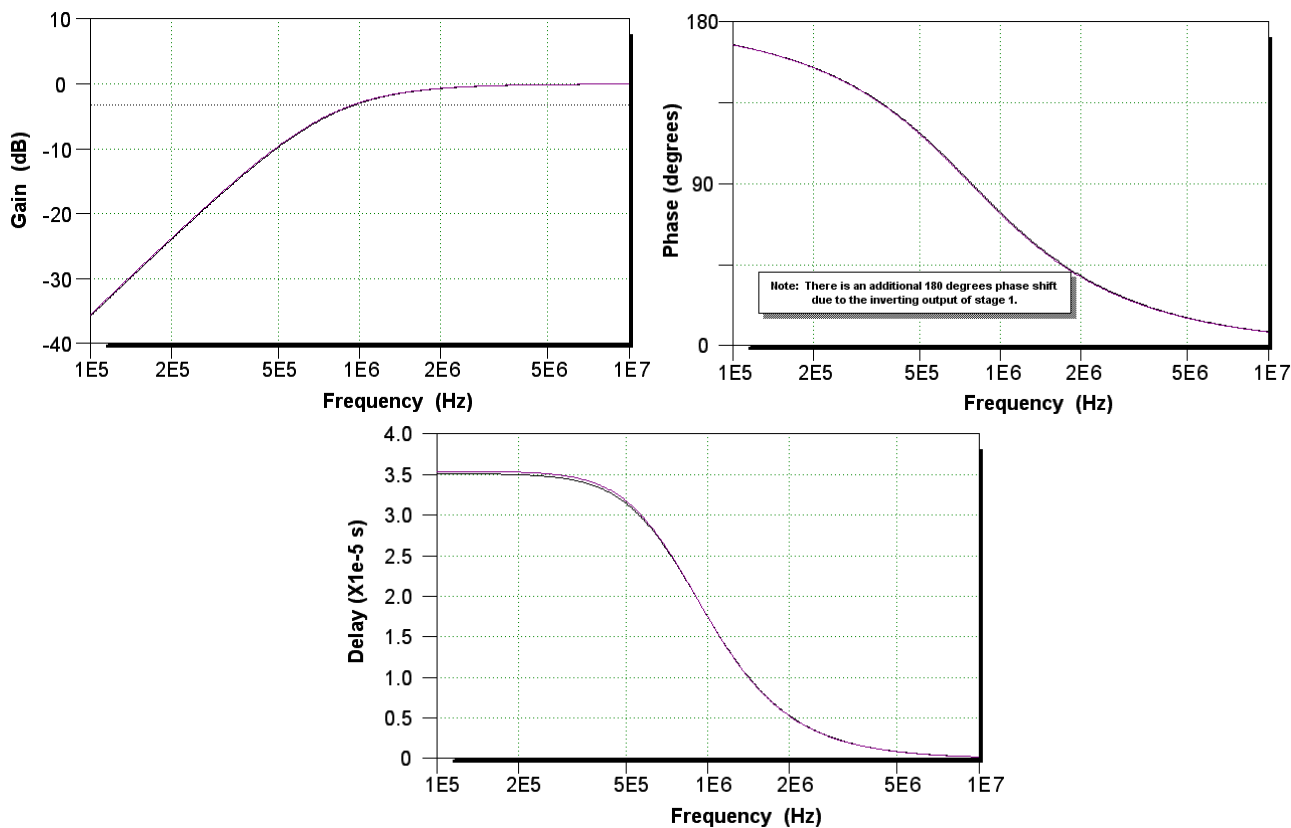


Figure 7. Example Filter Response

Two responses are plotted – although they are hard to distinguish because they are close together – black is the ideal response and purple is the response with actual 1% resistors. Group delay, as always, is most sensitive to component variation.

5 User's Guide for the *How do I select R's and C's for a Filter Circuit?* Spreadsheet

The KnowledgeBase item *How do I select R's and C's for a Filter Circuit?* contains a downloadable spreadsheet (Microsoft™ Excel), which is a design aid for selecting the optimum standard values of Resistance and Capacitance. Standard values are arranged in decade sequences, with the mantissa of values in each decade repeated in other decades. That means if there is a 102 Ω resistor, there will also be a 1.02 kΩ, 10.2 kΩ, 102 kΩ, 1.02 MΩ, and perhaps larger values. There will also be a 10.2 Ω, and perhaps even a 1.02 Ω resistor value available.

Standard resistor values are arranged in E increments related to tolerance. 1% resistors have 96 values per decade, and are referred to as E-96. Similarly, 5% resistors have 24 values per decade, and are referred to as E-24. 10% are E-12, and 20% are E-6. Some filter circuits, such as high Q notch and high Q bandpass require 1% capacitors to work properly. 1% capacitors are available in E-24 values.

To use the spreadsheet, click on the link from the KnowledgeBase. The spreadsheet will open in a Microsoft Excel Spreadsheet if Excel is installed on the computer and Internet Explorer is used as the web browser. If not, the file can be downloaded and opened in a program that can open Excel spreadsheets.

Enter a frequency into the indicated cell:

RC TIME CONSTANT CALCULATOR, Version 2

FREQUENCY: TOLERANCE (%)

1 to 999,999,999 Hz Capacitor (5 or 10)

Resistor (1 or 5)

MANTISSA	Resistor	Resistor	EXPONENT	Application
Capacitor			Capacitor	
6.8	3.9	8	-12	LOW POWER
3.9	6.8	7	-11	PRECISION
		6	-10	
		5	-9	
		4	-8	HIGH SPEED
		3	-7	
		2	-6	

SELECTED	MANTISSA	EXPONENT
RESISTOR:	3.9	5
CAPACITOR:	6.8	-9

ACTUAL FREQUENCY 60.01317613

ERROR 0.021960%

Figure 8. Entering the Frequency on the Spreadsheet

The frequency is the corner frequency for a lowpass or highpass filter, or the center frequency for a bandpass or notch filter. It can be entered in any format—the spreadsheet will convert it to the exponential format.

Next, enter the desired values of tolerance for the resistor and capacitor from the drop down menu in the indicated cells:

RC TIME CONSTANT CALCULATOR, Version 2

FREQUENCY: TOLERANCE (%)

1 to 999,999,999 Hz

Capacitor (5 or 10)

Resistor (1 or 5)

MANTISSA	Resistor	Resistor	EXPONENT	Application
Capacitor			Capacitor	
6.8	3.9	8	-12	LOW POWER
3.9	6.8	7	-11	
		6	-10	PRECISION
		5	-9	
		4	-8	HIGH SPEED
		3	-7	
		2	-6	

SELECTED	MANTISSA	EXPONENT
RESISTOR:	3.9	5
CAPACITOR:	6.8	-9

ACTUAL FREQUENCY 60.01317613

ERROR 0.021960%

Figure 9. Entering the Value of Tolerance Into the Spreadsheet

When the designer selects a 10% tolerance for the capacitor, it is understood that the design will be implemented with 5% tolerance (or better) capacitors. When 5% capacitors are selected, 1% capacitors are recommended for high Q notch and bandpass filters.

When the designer enters a frequency, the spreadsheet will calculate some sets of resistor / capacitor values:

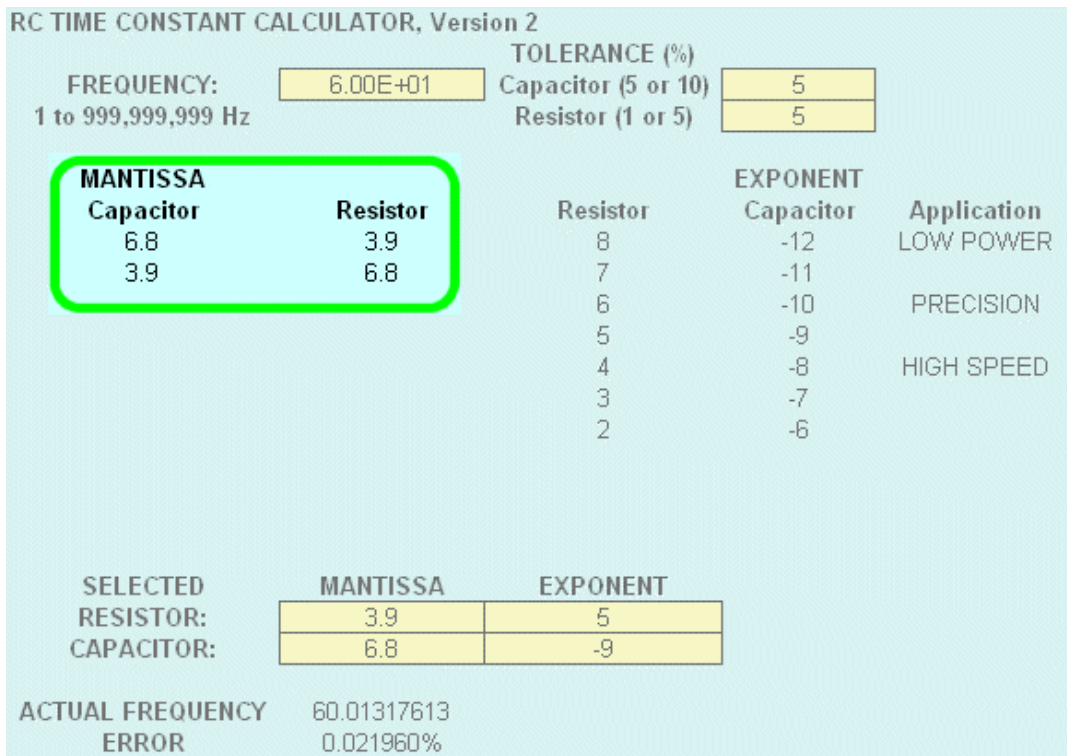


Figure 10. Mantissa Values Generated by Selected Frequencies

At the same time that the mantissa values are calculated, the exponent values of the resistor are also calculated (the capacitor exponent values are constant in the spreadsheet):

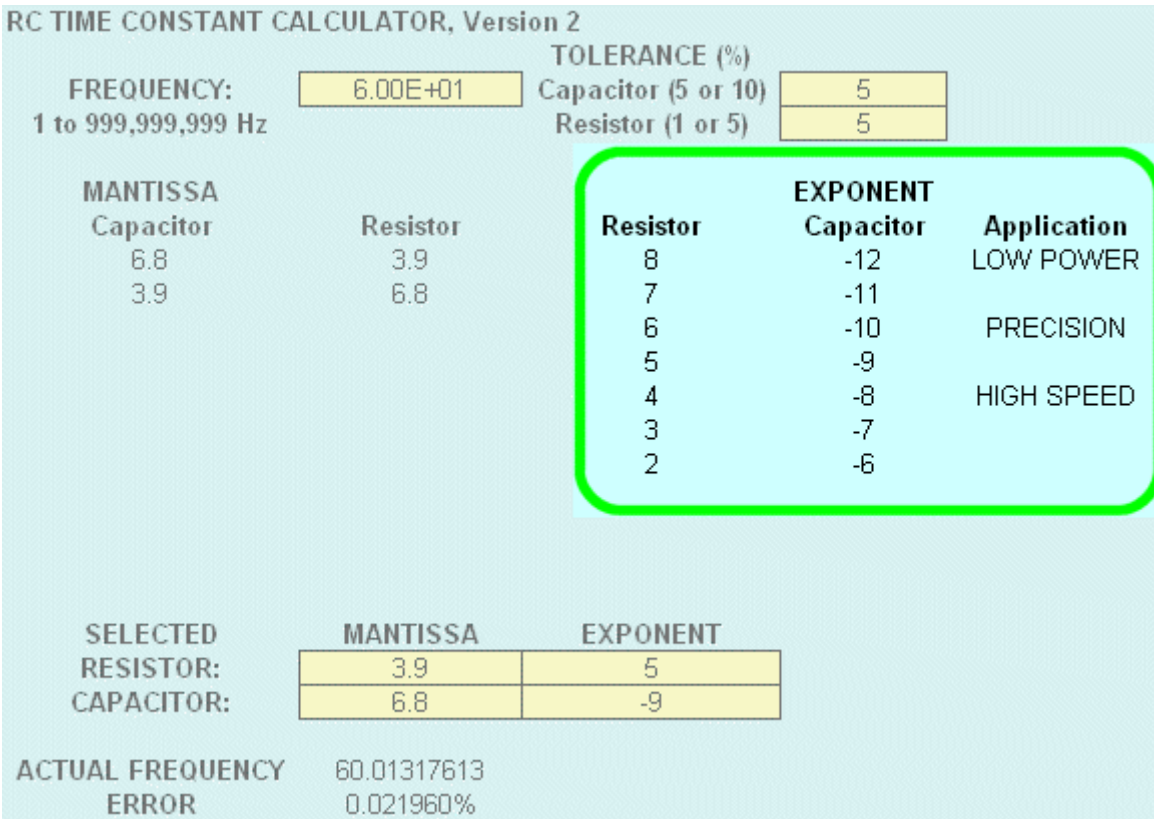


Figure 11. Exponent Values Generated by Frequency Entered

Designers now have the exact standard values for some sets of resistor / capacitor pairs that will make a filter with the desired corner or center frequency. Designers should select one set of mantissa values, based on the tolerance of parts available, and one set of exponent values, based on the tradeoff over power consumption, speed, and noise. They should be entered from the drop-down menus into the spreadsheet in the *Selected resistor capacitor* area:

RC TIME CONSTANT CALCULATOR, Version 2

FREQUENCY: 1 to 999,999,999 Hz

TOLERANCE (%)

Capacitor (5 or 10)	<input type="text" value="5"/>
Resistor (1 or 5)	<input type="text" value="5"/>

MANTISSA Capacitor	Resistor	Resistor	EXPONENT Capacitor	Application
6.8	3.9	8	-12	LOW POWER
3.9	6.8	7	-11	PRECISION
		6	-10	
		5	-9	
		4	-8	
		3	-7	HIGH SPEED
		2	-6	

SELECTED RESISTOR:

SELECTED CAPACITOR:

MANTISSA	EXPONENT
<input type="text" value="3.9"/>	<input type="text" value="5"/>
<input type="text" value="6.8"/>	<input type="text" value="-9"/>

ACTUAL FREQUENCY: 60.01317613

ERROR: 0.021960%

Figure 12. Selected Values of Mantissa and Exponent Entered on Spreadsheet

This will allow designers to do a double check on the values they selected, to make sure that there was no mistake. It will also calculate the frequency error, based on the mantissa and exponent values entered:

RC TIME CONSTANT CALCULATOR, Version 2

FREQUENCY: 1 to 999,999,999 Hz

TOLERANCE (%)
 Capacitor (5 or 10)
 Resistor (1 or 5)

MANTISSA	Resistor	Resistor	EXPONENT	Application
Capacitor			Capacitor	
6.8	3.9	8	-12	LOW POWER
3.9	6.8	7	-11	PRECISION
		6	-10	
		5	-9	
		4	-8	HIGH SPEED
		3	-7	
		2	-6	

SELECTED
 RESISTOR:
 CAPACITOR:

ACTUAL FREQUENCY
 ERROR

Figure 13. Frequency Error Generated by Selected Values

If all is well, the error will be small—meaning the values selected are correct.

This spreadsheet is offered as-is. Extensive testing has proven that it provides good values, although there is a slight possibility it might ignore some identical low error combinations in the E-96 / E-24 column. Texas Instruments assumes no responsibility or liability for the accuracy of results obtained.

6 Final Thoughts

When designing filters with the KnowledgeBase, designers should be aware of the following things:

- All op-amp filter circuits, particularly high speed, need decoupling capacitors on the power supply pins. They are not shown, because every application requires different values. **THINK**, do not just mount 0.1 μ F capacitors on the board!
- Single supply circuits require coupling capacitors to isolate DC potentials from other stages. This creates something of a dilemma for Texas Instruments applications – input capacitors mean that there are no true low pass filters. They all have high pass characteristics, and therefore are actually bandpass filters. Texas Instruments still calls them low pass filters, and advises designers to place the high pass pole below the lowest frequency of interest.

- There is no such thing as a high pass filter. No active op amp filter will be able to pass frequencies to infinity. The op amp itself, along with the characteristics of passive components, will ultimately limit the high frequency response. Therefore, all high pass filters are actually bandpass filters as well.
- Filter component values can be scaled. If resistors are increased by a factor of 10, capacitors can be decreased by a factor of 10. There are some guidelines for this:
 - Lower values of resistance and higher values of capacitance lead to less noise and higher speed – at the cost of power consumption.
 - Higher values of resistance and lower values of capacitance lead to less power consumption – at the cost of noise.
 - It becomes increasingly difficult to find precision resistors and capacitors in small values (under 100 pF for capacitors and under 100 Ω for resistors). Therefore, high frequency filters cannot be constructed with the precision of lower frequency filters.
 - It is difficult to find precision resistors above 10 M Ω . Therefore, very low power / low frequency filters may not be as accurate.

Filter component values can be scaled. If resistors are increased by a factor of 10

The KnowledgeBase item How do I select R's and C's for a Filter Circuit? contains a downloadable spreadsheet, which is a design aid for selecting the optimum standard values of Resistance and Capacitance. The component value selection is the exclusive domain of the designer. The KnowledgeBase can provide general guidance, but it is up to designers to make a judgment call based on the requirements of the system.

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