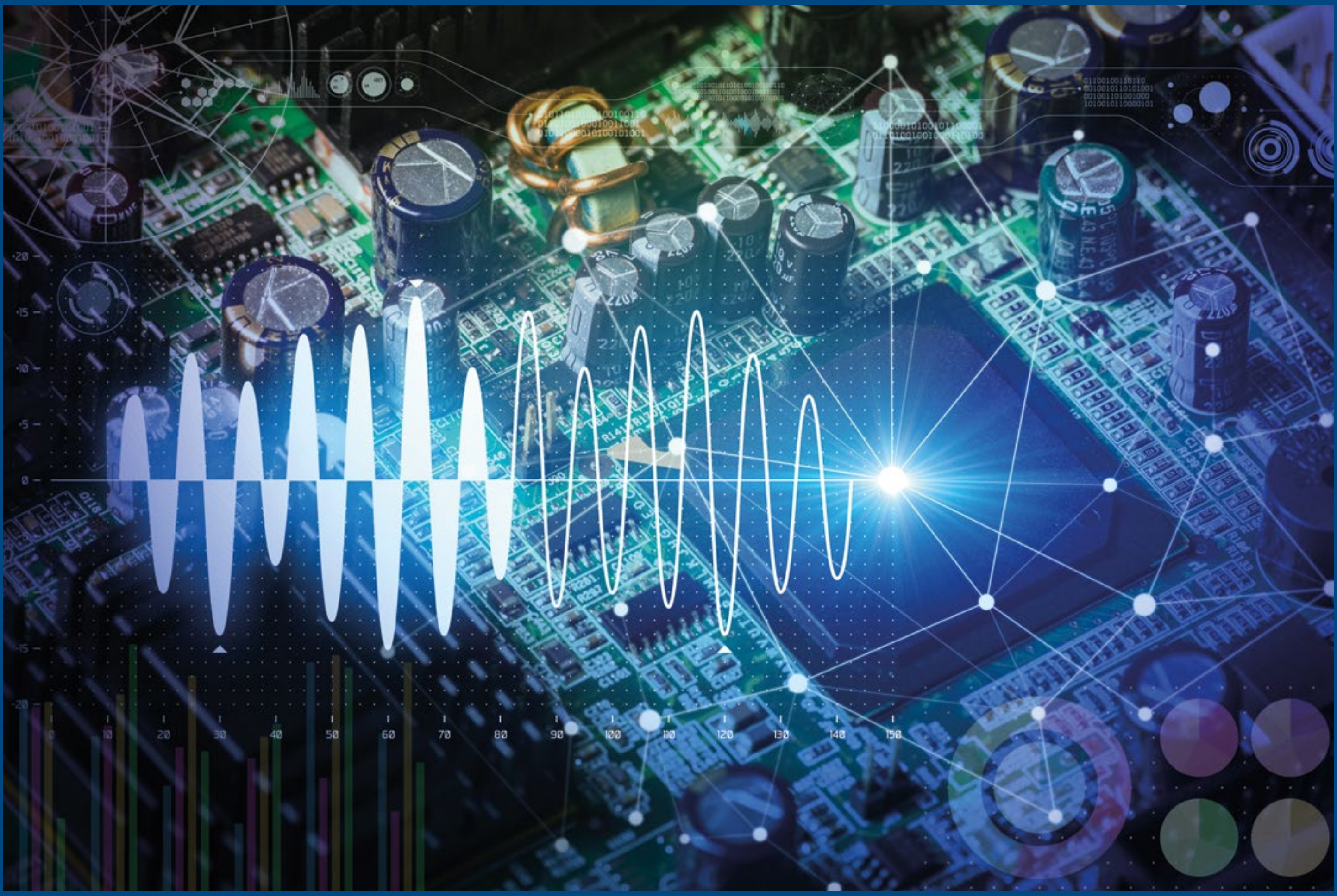
Understanding the Basics of Analog Design

By Mark Patrick, Mouser Electronics



Contents

Foreword

Analog design is a skill that is relevant to many engineers, but not necessarily well understood. With a shrinking pool of analog experts, there is a tendency for some engineers to think of analog design as something fundamentally different from the rest of electronics, with its own rules and jargon.

In this eBook, we aim to help change that perception, and to demystify analog design by providing an understanding of analog principles.

We'll start by reviewing the basics of analog circuit design and the tools that are available to engineers, enabling them to design with confidence. We will demonstrate that analog circuit design has evolved and now has a highly structured methodology. We'll explore some of the advanced hardware and software tools available that are helping to reduce the need for many complex manual calculations. And hopefully achieve our goal of encouraging more young engineers to look at analog circuit design as a highly valued and rewarding skill, and one that will further enhance their career development options.

MOUSER ELECTRONICS

The Importance of Analog Engineering Skills to the Electronics Industry

We hear phrases like "the digital economy" and "digital transformation" so often that they have almost become clichés. Industry's focus on digital technology means that many may forget that the real world is not digital, but analog in nature. The misperception that perhaps 'analog' technology is outdated and no longer relevant is having serious repercussions for the electronics industry, resulting in many undergraduate and graduate engineers opting to align their studies and research with digital electronics only.

This is creating a lack of understanding and practical experience of analog design and application skills among electronics engineers. This is made worse by the fact that many young engineers think analog circuit design is poorly defined, requires regular use of difficult mathematical calculations, and lacks the sophisticated software tools available to digital engineers. Unless this trend is quickly reversed, the electronics industry will soon reach a point where there are not enough engineers with analog experience for it to deliver innovation in line with consumer expectations.

In this eBook, we are aiming to redress the balance of knowledge and understanding of analog design.

What are 'Analog' and 'Digital'?

Analog refers to signals or information represented by a continuously variable physical quantity. Examples of analog quantities include voltage, light, heat, pressure and sound. In contrast, the digital representation of a quantity can only ever be one of a pre-defined number of pre-set (or discrete) values. The difference between analog and digital can be illustrated using the following simple examples:

- Turning the light in a room on fully or off (digital) versus using a variable dimmer switch to set the lighting to a desired level of illumination (analog).
- Using a thermostat that turns a heater fully on and fully off when the temperature in a room exceeds or falls below a pre-set value (digital) versus a thermostat that continuously adjusts the operation of the heater to keep the room temperature at a pre-set temperature (analog).
- An audio system with pre-set volume controls (digital) versus one with rotary control that allows the volume to be set to any desired level (analog)

The reason why analog quantities are converted into a digital form is that they can then be quickly processed by digital circuits. However, this does not mean digital signals are always the most accurate. Using the example of a thermometer, unlike its analog counterpart, a digital thermometer only measures temperature at periodic intervals – a process referred to as sampling. Secondly, it can only display that measurement using one of its pre-set values – a process called quantization.

Therefore, for the display on a digital thermometer (***Figure 1***) to update in response to a change in temperature, it must first perform its measurement (which may happen after the temperature change has already occurred), and secondly, the measured change must be bigger than the smallest pre-set value that it can recognize. Admittedly, the latest digital instruments are now designed to make many high-speed measurements and to recognize very small changes (due to having many discrete values). And while they can never be quite as accurate as their analog counterparts in pure measurement terms, their performance is usually sufficient for the application that they serve.

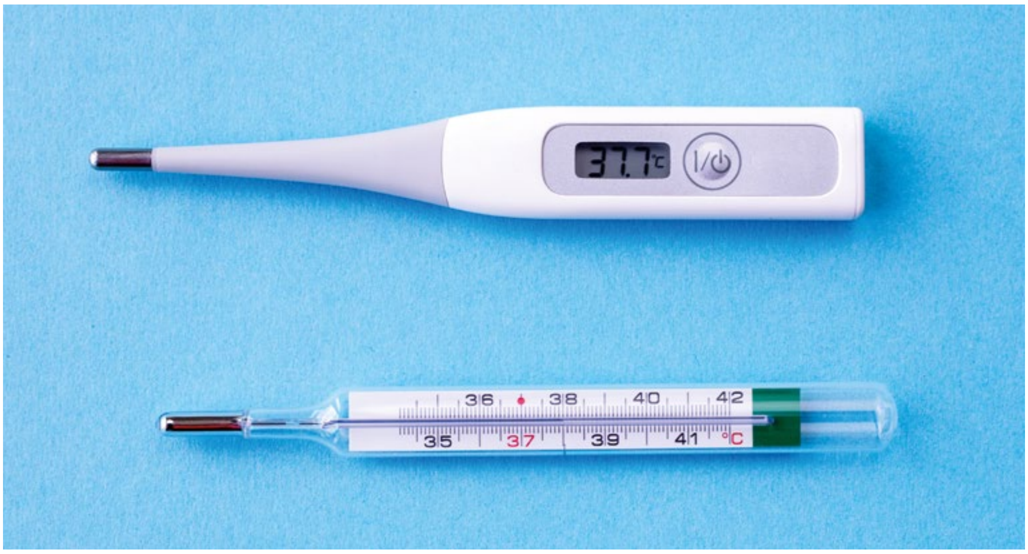


Figure 1 *Analog and Digital Thermometers*

Sensors and signal chain

A sensor (or transducer) is used to detect and convert one form of energy into another, for example capturing temperature, light, or sound, and converting it into electrical energy, usually in the form of an analog voltage signal. Sensors commonly used to detect temperature include thermocouples and resistance temperature detectors (RTD) while photodiodes are used to detect light, and microphones for sound.

Ultimately, most sensors operate on analog principles, and the electrical output signals that they produce are usually very small (millivolts or less). This means that their signal must be conditioned to remove noise and increase amplitude or level, before converting it into the digital form required by the downstream control system. The sensor and the circuitry used to do this conditioning are called the analog signal chain (amplifiers, filters, and data converters).

Signal Chain Basics

Let's look at the function of the analog signal chain, and review key component specifications.

Many of the electronic devices we use every day, and on which we've come to rely, simply would not function without the use of real-world input signals designed by electronics engineers.

What is the analog signal chain?

The analog signal chain (***Figure 2***) consists of four main elements: sensors, amplifiers, filters, and data converters (ADC). These are used to detect, condition, and convert analog signals into a digital format suitable for processing by a microcontroller or other digital control system.

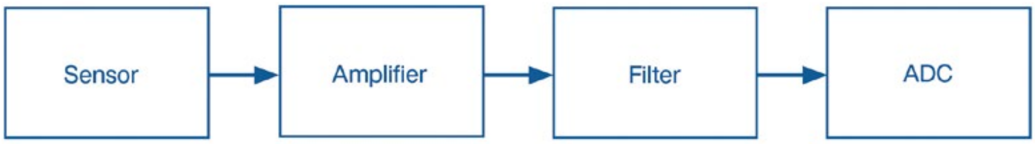


Figure 2 *Block diagram of the analog signal chain*

Sensors

The first part of the analog signal chain is the sensor (often called a transducer) which detects the input signal and converts it into electrical energy, usually in the form of an analog voltage or current. Sensors operate on a variety of physical principles. Some examples include:

- Temperature - Thermocouples and resistance temperature detectors (RTD)
- Pressure - Strain gauges or capacitive membranes
- Heart Rate - ECG electrodes
- Light - Photoresistors
- Sound - Microphones

For sensors with a voltage output, the range is typically from a few micro-volts (uV) to several milli-volts (mV), making the signal very susceptible to interference from sources of unwanted electrical noise. The noise can come from many directions but is broadly categorised as electromagnetic interference (EMI) or radio-frequency interference (RFI). To overcome this, the sensor output is usually measured as the difference between two terminals (differential) so that noise signals common to both are rejected.

Amplifiers

The second component in the signal chain is the (differential) amplifier, an electronic circuit that increases the magnitude of the sensor output by a scaling factor, A, according to the following formula, where A is called the gain.

$$V_{output} = A * V_{input}$$

The amplifier is needed because the sensor signal is typically too small to be converted into a digital format by the Analog-to-Digital Converter (ADC) at the end of the chain. The amplifier boosts the signal amplitude to a level that the ADC can effectively read. The maximum output voltage that an amplifier can produce is very close to the voltage level of its power supply.

Another engineering consideration that impacts design and component selection is the signal-to-noise ratio (SNR). Measured in decibels SNR is the ratio of signal strength compared to unwanted noise. A high SNR dB rating demonstrates a powerful signal which is more resilient against the effects of noise.

In many applications, a programmable gain amplifier (PGA) is used in conjunction with an automatic gain control circuit (AGC), dynamically increasing or decreasing the amplifier's gain if the magnitude of the sensor signal goes outside of its expected range (due to environmental or other reasons). If the sensor signal does go too high the amplifier could saturate - causing it to attempt to produce an output signal higher than is physically possible.

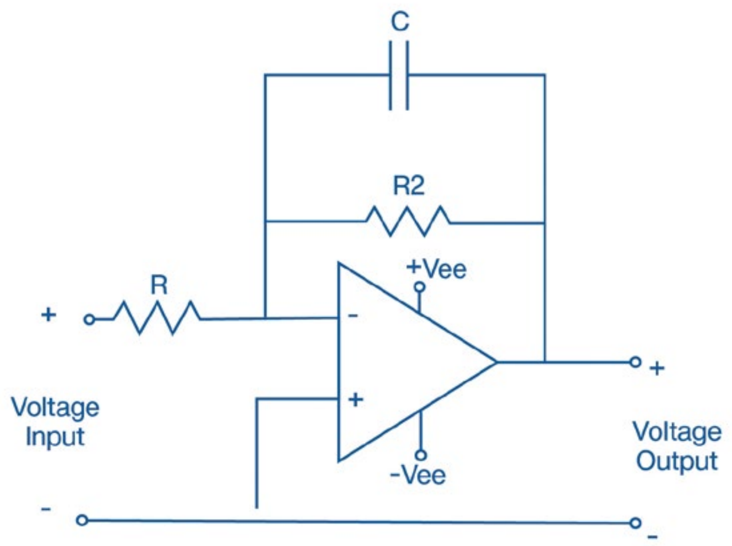


***Figure 3** Low pass filter circuit using an op-amp*

Filters

Once amplified, the sensor signal must then pass through an analog filter circuit to remove any unwanted frequency components. The three main categories of analog filter circuits are:

- Low-pass filter (removes high-frequency signals)
- High-pass filter (removes low-frequency signals)
- Band-pass filter (only allows signals within a defined range to pass through)

Filter circuits are constructed using a combination of capacitors, resistors, and an operational amplifier (Figure 3).

Filter key performance specifications include:

- **Filter bandwidth**, which describes the range of frequencies that a circuit allows to pass through with no reduction in amplitude (attenuation), with the 3dB corner frequency (or frequencies) being the power at which the output signal falls to half the power of the input signal.
- **'Roll-Off'**, which describes the rate of attenuation - this is how quickly the filter discriminates against unwanted frequency components at the input and is measured in decibels/decade. Filters with faster roll-off require more components, increasing complexity and cost.
- **'Phase'**, which refers to the relative delay between the input and output signals is important if a feedback loop is being used in the signal chain, as it can affect loop stability.

Analog to Digital Converters (ADCs)

The final component sitting between the analog and digital signals is the analog-to-digital-converter (ADC). For an ADC to produce an accurate digital representation of the analog signal, it must sample at twice the highest frequency component of the signal (called the Nyquist frequency). This is performed using a 'sample-and-hold circuit which periodically measures the analog input voltage and holds it at a constant level long enough for the ADC to perform the conversion, before then moving on to the next sample.

The next step in the conversion process is 'quantization' where the sampled voltage is compared to a fixed number of discrete values, each represented by a unique digital code. For example, a four-bit ADC has sixteen (24) discrete levels available to represent a sample. ADCs with more bits have better resolution (accuracy) since they use more discrete values, with resolution doubling for each added bit. The most common ADC architectures include:

- Successive Approximation Register (SAR)
- Sigma Delta
- Flash
- Pipelined

Conclusion

The analog signal chain is the series of circuits needed to accurately detect, condition, and convert analog signals into a digital form. With a solid grasp of signal chain basics, engineers can design products that deliver reliable and effective performance. The electronics industry depends on electronics engineers with the necessary knowledge and experience of analog circuits, to design products that deliver reliable and effective performance.

Analog Design Tools and Resources

What lab equipment do electronics engineers need to perform their role? For a start, there are familiar hardware tools – the power supply, signal generator, and oscilloscope. Today, their once discrete functionalities have now been combined into a single, convenient USB powered tool. Engineers can also take advantage of software tools that have greatly simplified the process of designing analog filter circuits.

Laboratory Equipment When Working with Analog Circuits

The purpose of an electronic circuit is to control and direct electric current to deliver a variety of functions. For testing the performance of any analog circuit design a power supply is a critical tool.

A power supply (***Figure 4***) operates by rectifying an ac voltage to generate pulsed dc, which is filtered producing a smooth voltage. This voltage is then regulated, creating a constant output level that is unaffected by changes in ac input voltage or circuit loading.

In a lab environment, electronics engineers use a benchtop DC power supply (which may have additional features, depending on specification) to re-create the power source that a circuit will use in a field application. Using rotary controls allows the regulated DC voltage and current outputs to be set more precisely. Some standalone power supplies are programmable, meaning they can be connected directly to a laptop computer which can then control them.

Figure 4 *Laboratory power supply*

Figure 5 *Signal generator*

A **signal generator** is used to create repeating or non-repeating waveforms, allowing engineers to select the size, shape, and frequency of the test signal required. Sine, triangular and square wave options are typically provided, with pushbuttons to select frequency control and rotary controls to tune amplitude. Higher specification models are programmable and may also include an LCD screen.

Visualising Analog Signals

Traditionally, engineers have used an oscilloscope; a large benchtop instrument with an LED screen to view analog signals. However, new types of ultra-portable devices, like the Digilent Analog Discovery 2 combine the functionality of an oscilloscope, signal generator, DC power supply, and voltmeter, packaged within a compact footprint. These 'USB connected' devices are easily configured using a laptop computer, which can also be used for signal display. Form and functionality make these kit solutions ideal for engineers to perform tests and signal analysis virtually and in any environment.

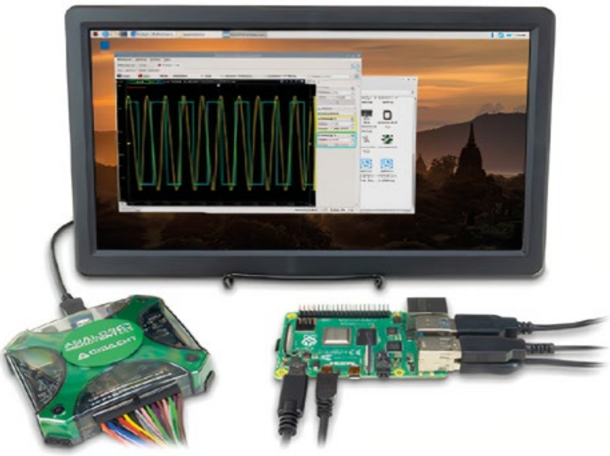


Figure 6 *Digilent Analog Discovery 2*

Designing Filter Circuits

Once an engineer has established their filter circuit specifications, they then determine the circuit configuration needed to achieve it. Traditionally, this required them to mathematically calculate the filter's transfer function (equation) then select the components (capacitors, resistors, and op-amps) to build it. This can be a time consuming and sometimes difficult task, but has been greatly simplified by the availability of software tools like Analog Filter Wizard from Analog Devices, which allows the electronics engineer to design a filter circuit in five simple steps:

Step 1: Select Filter Type

Choose the type of filter required (low-pass, high-pass, or band pass)

Step 2: Specifications

The 'Specifications' tab allows them to input the gain, passband, stopband, and filter roll-off and to investigate the trade-off between speed versus the number of stages, using a slider. The tool also displays a graph of the filter's frequency response, which immediately updates when input specifications are changed.

Step 3: Components

The 'Components' tab displays the circuit configuration and physical component values (R, C, and Op-Amp) required to meet the filter specification.

Step 4: Tolerances

Here engineers can specify the tolerances of the circuit components they choose. While lower tolerance components can cost less, and be more readily available, they may increase variability between individual filter instances. This trade-off between cost, performance, and availability should be fully considered by applying "design for manufacture" - a strategy that mitigates the potential risk of incorrect component specification early in the design process.

Step 5: Next Steps

This allows the engineer to download SPICE files for the filter circuit – a useful feature that allows them to simulate the 'real-world' performance of the filter circuit.

Circuit Simulation

SPICE software tools allow the simulation of circuit behaviour in practical applications. By modifying variables such as the power supply voltage and temperature, engineers can determine the tolerances which are acceptable to each circuit well before committing to building a physical prototype - both costly and time-consuming. Electronics engineers can also specify a variety of input signals, voltage/ temperature variations, and simulation types that allows them to analyse circuit behaviour in terms of both time and frequency.

Conclusion

The latest generation of hardware and software tools greatly simplify tasks commonly performed by electronics engineers when designing analog circuits. The functionality of the power supply, signal generator, and oscilloscope have been combined into standalone, ultra-portable instruments like Digilent's Analog Discovery 2. While the process of designing an analog filter circuit has been made easier by the availability of software tools like Analog Filter Wizard by Analog Devices.

Getting to Grips with Analog Design

Many engineers need to quickly design a fully functional analog filter circuit, but would much rather do this without manually calculating component values, using complex numbers or differential equations. Utilising free software tools like Analog Filter Wizard and LTSpice, both from Analog Devices, electronics engineers can now design and simulate the behaviour of a filter circuit, before committing to building it in the lab or applying it in a test application.

The Design Challenge

The frequency of human speech is approximately between 300Hz and 3kHz. The challenge is to design a bandpass filter (BPF) that will allow signals within this range (the passband) to pass through the circuit while rejecting frequencies outside this frequency range (the stopband). A practical application for this filter is in the telephone system to band-limit the signal before it is digitized using an Analog-to-Digital Converter (ADC)

Building the Circuit

First, start the Analog Filter Wizard tool and select a Band Pass Filter from the choice of options (***Figure 7***).

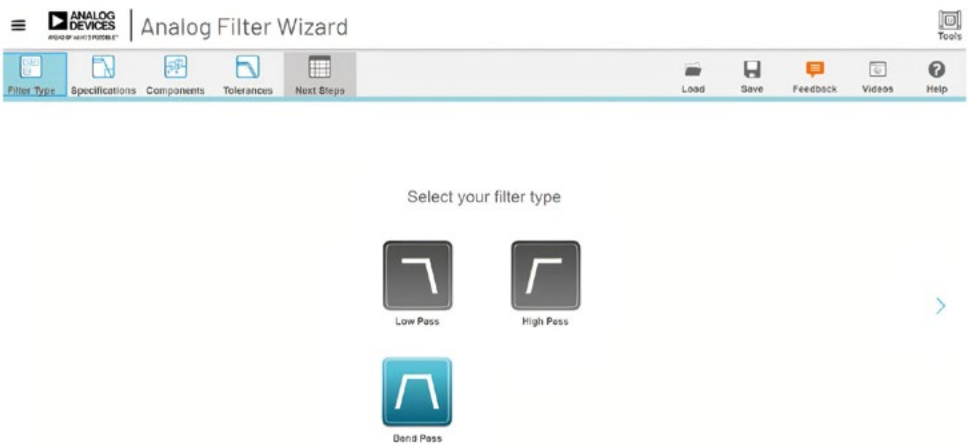


Figure 7 *Filter type menu*

Next, open the '**Specifications**' tab to display a user-friendly graphical user interface (GUI) that allows the engineer to input filter specifications and then plots a graph of the corresponding filter frequency response. For this example, the values shown in ***Figure 8*** generate a frequency response that closely matches the desired filter behaviour.

The passband is defined as the range of frequencies for which the output signal is at least 70% of the magnitude of the input signal and is indicated by the blue shaded area between the two -3dB 'corner' frequencies. The filter 'roll-off is specified to be -40dB/decade which means signals whose frequencies are 10 times higher (or lower) than the two corner frequencies of 300Hz and 3kHz respectively, are attenuated (reduced in magnitude) by a factor of 100.

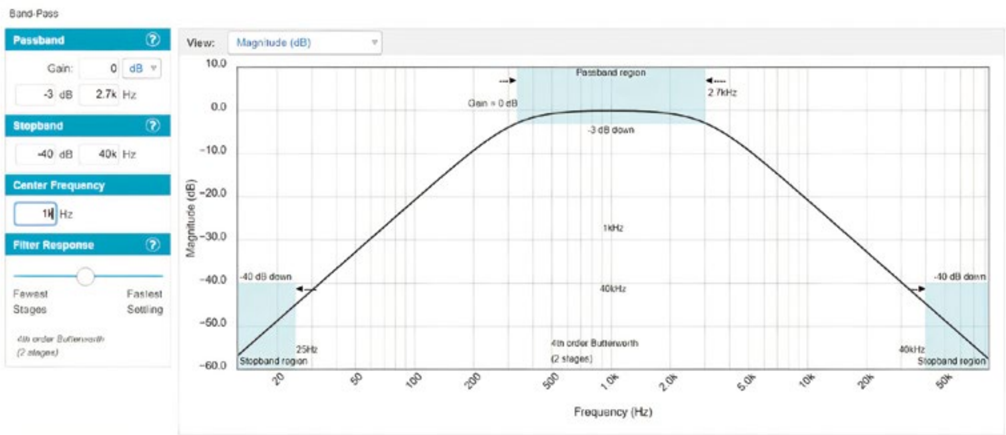


__Figure 8__ BPF frequency response

On the '**Components**' tab, the elements required to build the filter are displayed. There is the option to add the voltage levels the circuit will use and select custom component types (resistors, capacitors, op-amp), or simply accept the default components selected by the tool.

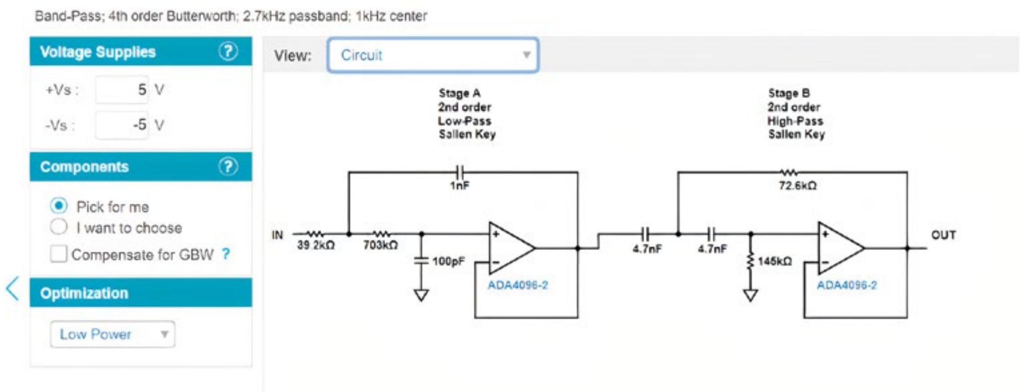


__Figure 9__ BPF Circuit components

The circuit configuration shown is for a fourth order Butterworth filter which comprises of a second order low-pass Sallen-Key filter and a second order high-pass Sallen-Key filter. In combination, they provide the desired bandpass frequency response.

Using the '**SPICE Only**' function (under the 'Next Steps' tab), engineers can download the software files needed to simulate the circuit using the LTSpice simulation tool, which can be downloaded from Analog Devices' website.

Define Input Signals

Figure 10 shows the LTSpice schematic shown after the 'TransientAnalysis.asc' file (provided by Analog Filter Wizard) is opened. The two second order filter stages, power supplies (V2, V3) and input signal source (VIN) are clearly visible.

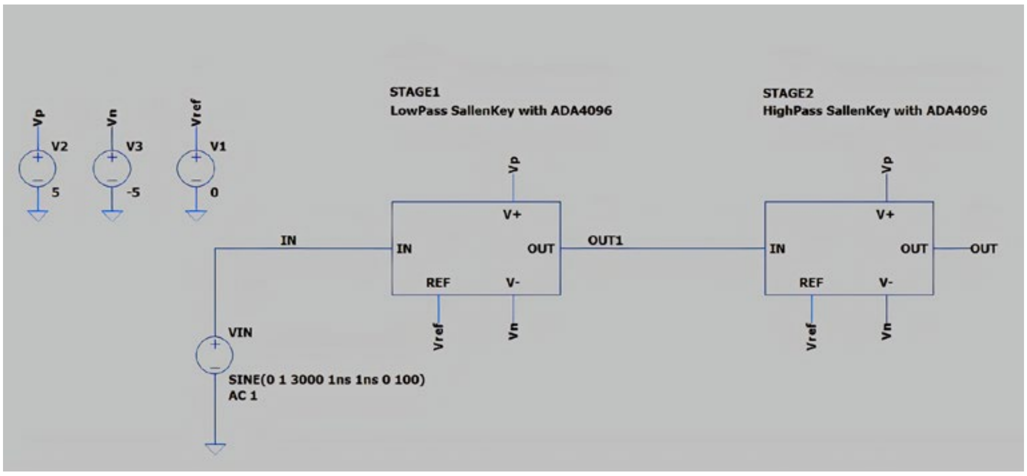


Figure 10 *LTSpice BPF simulation schematic*

Designers can quickly perform two types of simulation to verify that the filter design behaves as specified

- Transient Analysis
- AC Analysis
- The transient analysis simulates the filter behaviour for a real-world time domain signal with a specified input voltage and frequency. The maximum input voltage must be within the operating voltage of the op-amps chosen.

AC analysis simulates the filter behaviour across the full range of possible input signal frequencies.

Simulating the Circuit and Examining the Output

For the transient analysis, the input signal is a 1V (peak) sine wave with a frequency of 1kHz. ***Figure 11*** demonstrates that the signal passes unattenuated through the filter since the input (green trace) and output signal (blue trace) are almost indistinguishable. This behaviour is expected since 1KHz lies within the filter's passband.

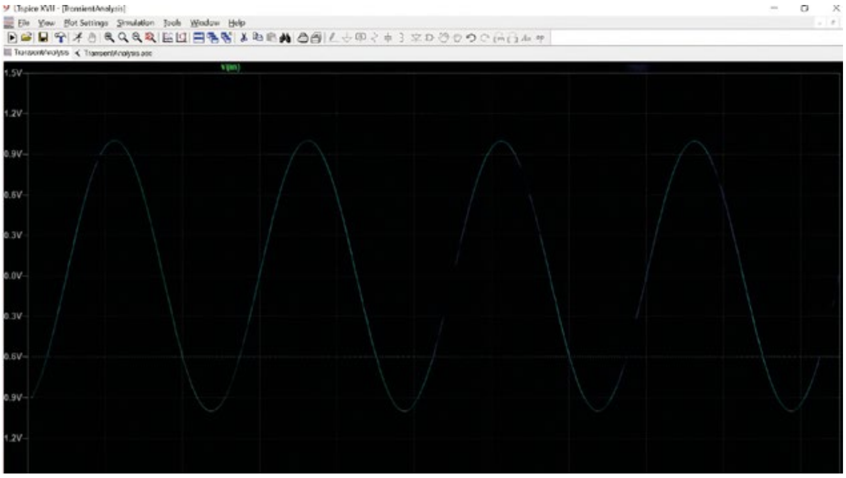


Figure 11 *1KHz time domain signal passes unattenuated through the filter*

Re-running the same simulation for an input signal with a frequency of 30kHz (***Figure 12***) shows the output signal to be almost 0V – again this is the expected behaviour as this frequency is outside of the passband (stopband).

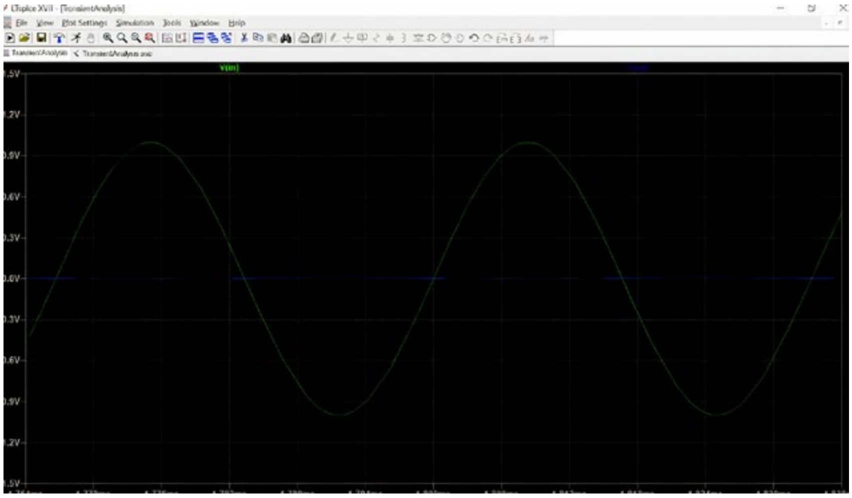


Figure 12 *Filter rejects a 30KHz time-domain signal*

The testbench schematic for the 'ACAnalysis.asc' file downloaded from Analog Filter Wizard is shown in ***Figure 13***.

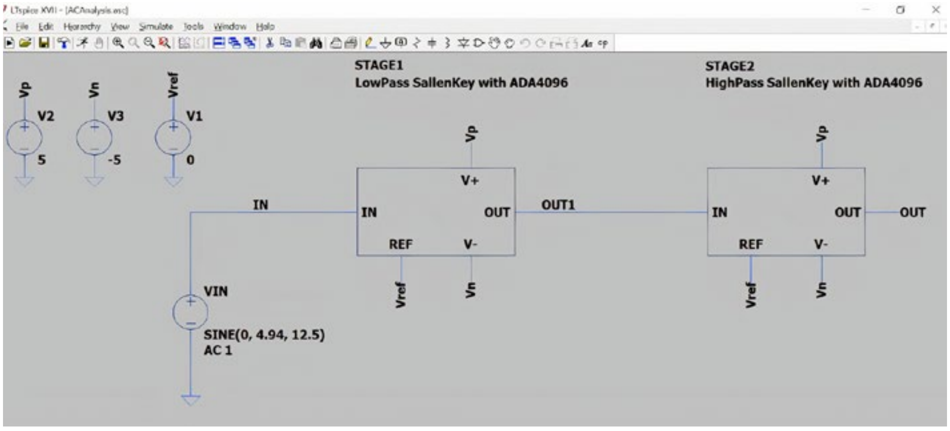


Figure 13 *LTSpice AC analysis testbench*

Figure 14 shows the frequency response of the filter generated by the AC analysis which closely matches that shown when specifying the filter performance in Analog Filter Wizard (***Figure 3***).

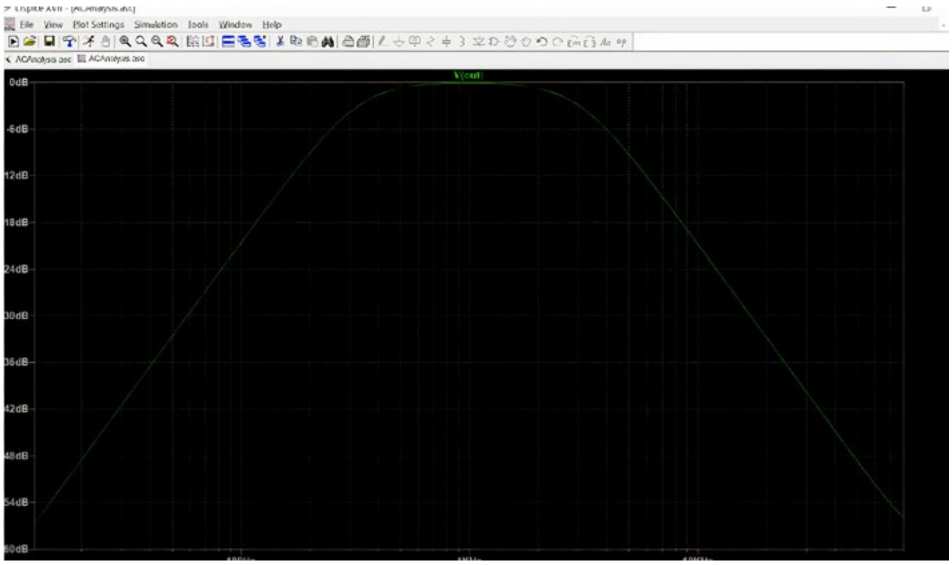


Figure 14 *BPF filter frequency response*

Conclusion

Throughout this ebook, our goal has been to increase awareness of the shortage and need for electronics engineers with analog design skills. We reviewed the basics of analog filter design and the tools that electronics engineers use to do their job. Far from being a design principle that relies on the subjective insight of the individual engineer, analog circuit design has evolved into a highly structured methodology.

This is greatly simplified by the availability of advanced hardware and software tools that automate tasks previously requiring time-consuming manual calculations. Hopefully, any new engineers reading this will look at analog circuit design in a different light, and see it as a highly valued skillset and a rewarding career option.