Experiment 5

Active filters and tuned amplifiers

5.1 Active filter

Weak signals require special attention. The techniques of separating signal from noise vary depending on the nature of the signal and of noise. There are no general easy prescriptions.

When the frequencies of the signal and of the noise differ, one way to increase the signal–to–noise (S/N) ratio is to restrict the bandwidth of the amplifier in such a way that only the signal frequencies are transmitted. This principle is illustrated using an active filter device.

The AF100 universal active filter is a versatile active filter device. It has high–pass (HP), low–pass (LP), and band–pass (BP) outputs simultaneously available and an uncommitted summing amplifier for making notch filters. The centre frequency is tunable from 200 Hz to 10 kHz with two resistors. The quality factor (Q) is variable from 0.01 to 500 by changing two additonal resistors. The AF100 can be used in either an inverting or a non–inverting configuration.
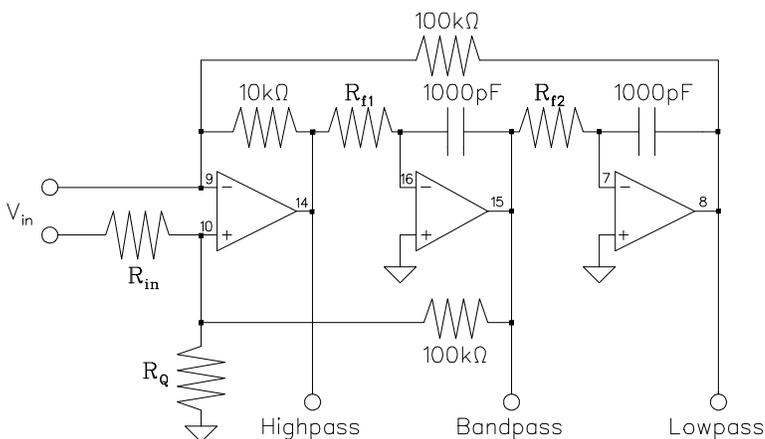
The pinout and the schematic diagram of an AF100 are as shown. R_{in}, R_Q, R_{f1}, and R_{f2} must be supplied externally to AF100 (see below). All other components are internal.

The gain and Q value of the filter are determined by R_{in} and R_Q. The centre frequency of the filter is determined by identical resistors, R_{f1} and R_{f2}, according to

$$f_0 = \frac{50.33 \times 10^6}{R_f}, \qquad \text{in Hz}$$
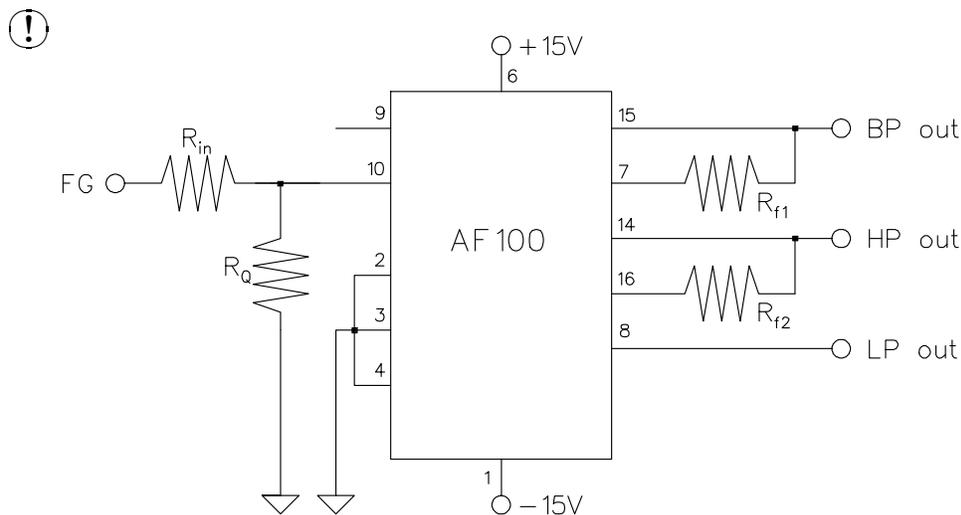
Wire up the non–inverting mode filter using external resistors of $R_{f1} = R_{f2} = 100k\Omega$ and $R_{in} = R_Q = 100k\Omega$. Use precision resistors if possible.

(!) These external resistor values should give a centre frequency of ~ 500Hz and a Q of slightly greater than unity. Connect the FG output to R_{in} and use the scope in the two–channel mode to observe both the FG output and the bandpass output of the filter. Connect the FG TTL output to the digital counter for a readout of frequency. Set the FG for a 1V peak–to–peak sine wave. Observe the bandpass output as the FG frequency is varied through the centre frequency, f_0.

(?) What happens to the bandpass output at f_0?

(!) To measure f_0 accurately, switch the scope to produce an xy–plot (Lissajous figure) of filter output *vs.* filter input. At the centre frequency the bandpass output should be exactly 180° out of phase with the input signal. Use the Lissajous figure to adjust the FG exactly to the centre frequency (see Experiment 1, and/or *Malmstadt* p.43 or *Brophy* p.63, for a discussion of Lissajous figures).

(!) Now switch the scope back to the dual trace mode and measure the peak–to–peak output voltage of the bandpass filter as a function of FG frequency over a range of 20 Hz to 20 kHz. Record 10–15 values in this range including several near f_0.

(!) Calculate and plot the filter gain in dB *vs.* log frequency.

(?) From the graph, determine the rolloff rate of the filter in dB/decade, on both sides of f_0.[1] Comment on the values you obtain.

(!) Now connect the scope to the low–pass filter output. Convince yourself that the device acts as a low–pass filter. Accurately measure and record the 3 dB frequency where gain $G = 0.707 \times G(\text{lowfrequency})$, and the phase shift at the 3 dB frequency.

(!) Repeat for the high–pass filter output.

(!) To get a filter with a higher Q, use $R_{in} = 20\,k\Omega$ and $R_Q = 1\,k\Omega$. Set the FG to give a sine wave with $V_{p-p} \simeq 0.5$V. Observe the bandpass output.

(!) Measure and plot the gain in dB *vs.* log frequency for the high–Q bandpass filter.

[1]A useful `physica` trick: fit `G=(a*f+b)*(f<=480)` will only fit $G(f)$ for values of $f = 480$ and below.

? Estimate the Q of the two bandpass filters you have investigated. Q can be measured as the ratio of the centre frequency f_0 of the bandpass output to the bandwidth (the difference in frequency between the upper and the lower $3\,dB$ points).

! Return the AF100 to the low–Q state, ($R_{\text{in}} = 100\text{k}\Omega$, $R_Q = 100\text{k}\Omega$). Vary the feedback resistors and measure the centre frequency of the bandpass output.

$R_{\text{f1}} = R_{\text{f2}}$	f_0, predicted	f_0, measured	% error
10kΩ			
50kΩ			
200kΩ			

5.2   Notch filter

A special form of active filtering can be thought of as the reverse of bandpass filtering. In analyzing a notch filter *we concentrate on the noise rather than the signal.*

!
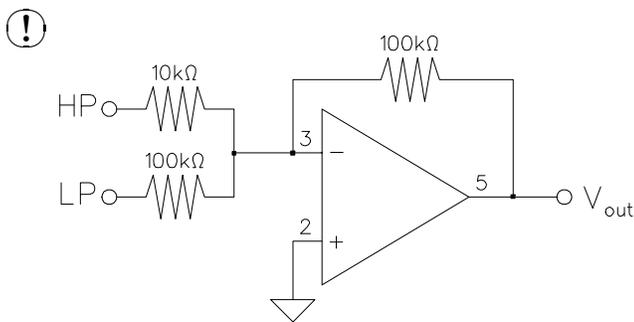
AF100 has one additional, uncommitted, summing op–amp. It can be used to construct a notch filter by summing the low and high–pass outputs, as shown.
Wire up the above circuit. **Make sure you disconnect the grounding wire from pin 3!** Set the AF100 to $f_0 = 500\text{Hz}$.

! Measure the frequency response of the notch filter. Choose the frequencies of the FG wisely: take a sufficient number of measurements to resolve the shape of the filter's transfer function.

! Plot the gain *vs.* log frequency.

? What type of noise could be reduced using the notch filter?

? Determine f_0 from your plot. How does it compare with the expected value?

5.3   Lock–in amplifier

One of the best ways to dicriminate against noise is to use a lock–in amplifier. It combines the techniques of signal modulation at the source, band–pass limitation, and phase–lock demodulation to provide ability to distinguish weak signals "buried" in the noise. Because they actively modulate the source signal, lock–in amplifiers are capable of distinguishing signal and noise that have overlapping frequency spectra.
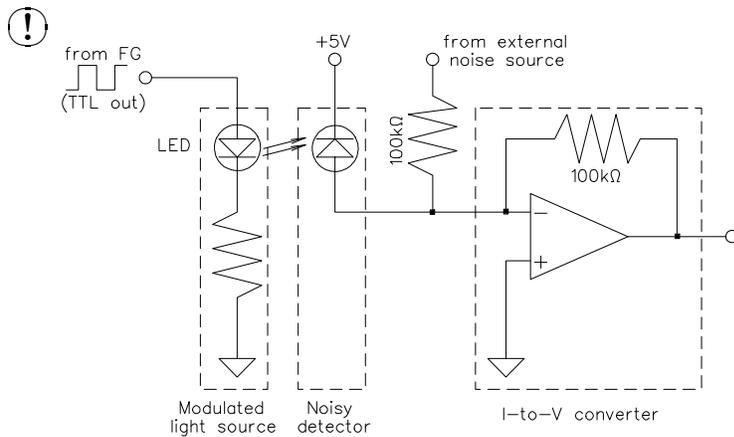
Connect a biased photodiode or a phototransistor to a I–to–V–converter. Connect an LED to the TTL output of the FG set at about 500 Hz. Do not connect the external noise source (NM on the job board) yet.

Use the scope to observe the output of the converter and adjust the position of the photodiode and/or the gain of the amplifier until the square–wave component of 50 to 100 mV is obtained at the output.

Make note of the DC level, the square–wave amplitude (p–p), and the approximate noise amplitude (p–p) in the output signal.

? Why is there a DC component in the output of the I–to–V–converter?
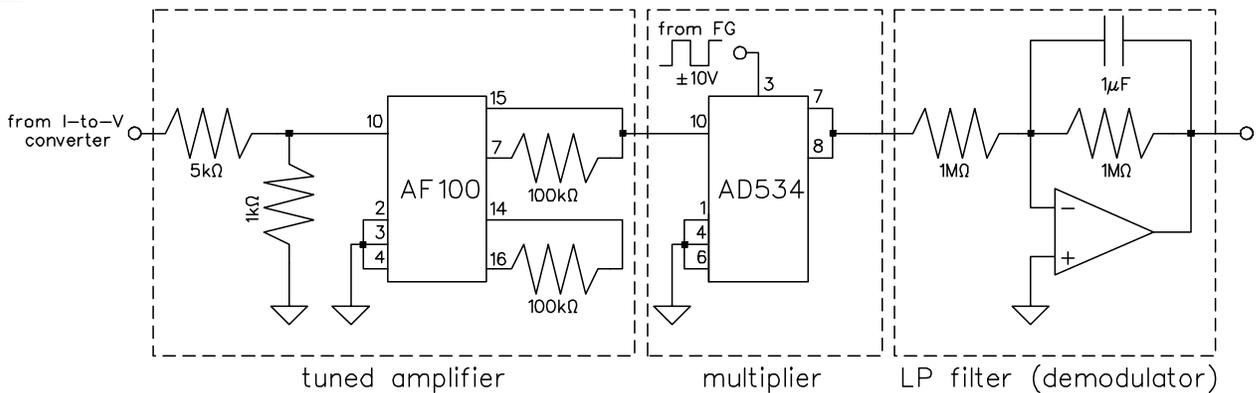
! Now connect the AF100 tuned amplifier circuit to the output of the I–to–V converter. Observe the tuned amplifier output with the scope. Adjust the FG frequency to get the maximum output from the tuned amplifier. Record your values of tuned amplifier output voltage (p–p), waveshape appearance, DC component of the output voltage, and the FG frequency setting.

? You should have observed a sine wave at the tuned amplifier output. The input, however, was a noisy square wave with a DC component. Explain the difference in input and output waveforms.

! The analog multiplier and low pass filter (phase–locked demodulator) should now be connected. The tuned amplifier output is multiplied by a square wave that is synchronous with the LED modulation. Adjust the FG square wave output to supply a ±10 V reference signal to the multiplier. Observe the multiplier output. Adjust the FG frequency carefully to obtain a waveform that most closely approximates a full–wave rectified sine wave. Draw the observed multiplier output waveform. Label the axes.

! Connect the active low–pass filter to the multiplier output. Observe the DC output with the scope. Record the DC level observed with the modulated LED on and off.

! Look again at the I–to–V converter output and measure the ratio of the square–wave amplitude to noise amplitude.

? Calculate the signal–to–noise (S/N) ratio improvement obtained with the lock–in amplifier.

(!) To better demonstrate the noise rejection capabilities of the lock–in amplifier, still more noise will be intentionally added to the signal. This noise will be obtained from the noise generator circuit available on the reference job board.
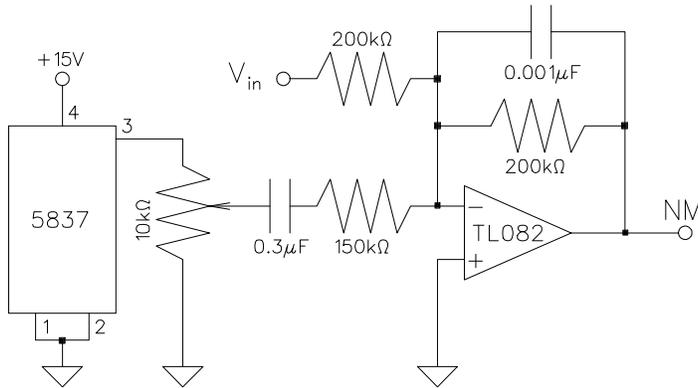
The relevant part of the reference job board circuit is shown. The 5837 digital noise generator IC produces 10 V pulses that have varying durations. The pulse durations are random integer multiples of $20\,\mu s$. The $10\,k\Omega$ potentiometer selects a fraction of the noise generator output amplitude. The noise signal is AC–coupled into a summing amplifier that also serves as an active low–pass filter.

The additional input to the summing amplifier allows the noise generator signal to be added to another signal: $V_{NM} = V_{in} + \text{noise}$

Vary the $10\,k\Omega$ potentiometer to obtain maximal noise amplitude. Sketch the waveform observed on both sides of the coupling capacitor and at the output of the summing amplifier. An oscilloscope time base of $20\,\mu s$/div is recommended.

Also observe the output of the summing amplifier at a sweep speed of $500\,\mu s$/div. This output is labelled NM on the job board, for Noise Mixer output.

[?] Calculate the cut–off frequency of the low–pass filter in the NM. What is the attenuation of this filter for the frequency component that results from transitions every $20\,\mu s$ (25kHz)?

(!) Connect the NM output through a $100\,k\Omega$ resistor to the summing point of the I–to–V converter (in the noisy signal source). Observe the converter output with a scope and adjust the noise generator output from zero until the square wave becomes difficult to see. (Trigger the scope from a clean square–wave or TTL output of the FG to avoid loss of synch.) Measure the DC output voltage of the lock–in amplifier, with the modulated LED on and then off. Compare again the signal–to–noise (S/N) ratios at the input and output of the lock–in amplifier.

[?] Explain why it is necessary to modulate the signal in order to obtain the improvement in S/N through the lock–in technique.