Lab 6: Sallen-Key Low-Pass Filter

Goal: We are going to design, build and test the Sallen-and-Key filter that we need in the ultrasound velocity sensor board

1) Overview of ultrasound system

Here's a three-sentence description of the system. The transmitter transducer sends out a 40 kHz ultrasound wave that bounces off a moving object, the frequency of the reflected wave will change via the Doppler effect. We detect the reflected wave via the receiver transducer, and measure the frequency difference between the reflected wave and the transmitted wave, thereby determining the velocity of the object.

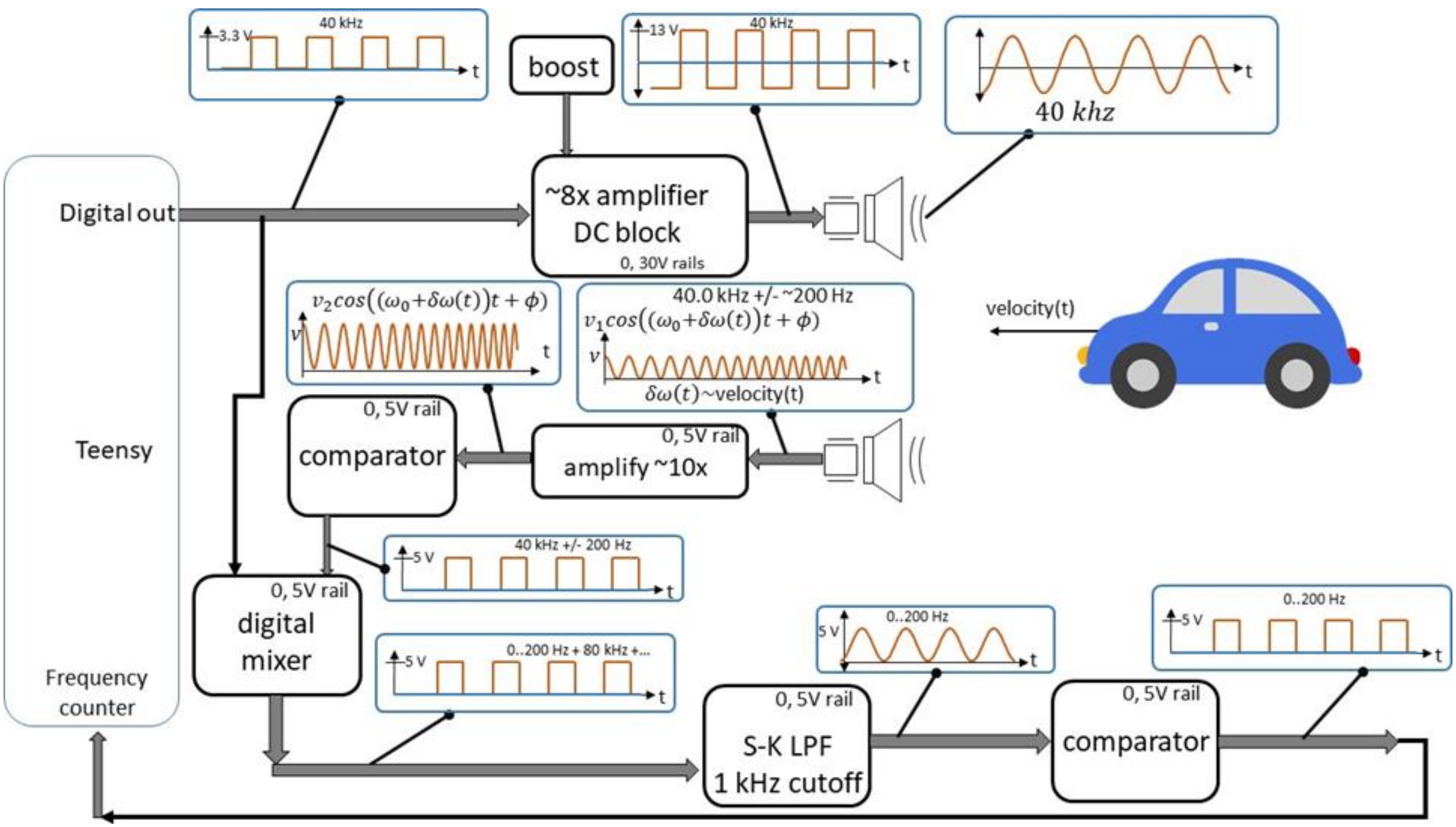


Figure 1: System Block diagram

First, let's recall again what we're trying to do with the Doppler ultrasound system, and what we've done so far.

- In the first stage, we used Teensy to create an ultrasound transmit signal (40 kHz square wave), and then we used an op-amp to amplify it.
- That ultrasound signal bounces off an object. If the object is moving, then the frequency of the reflected ultrasound wave changes by a little bit δf via Doppler Effect.
- In order to measure this frequency difference δf, the received signal was amplified with an approximate gain of ten (10).
- Then we turned the amplified received signal into a digital (square) wave to make it easier to manipulate. The comparator does this. We can do this because the information we care about is the frequency of the signal, which remains unchanged as a digital (square) wave.
- Then, we multiplied the received signal with the original transmit square wave using an XNOR gate.
- You'll recall from Lab 5, that this created a signal with two main frequency components, one at δf, the Doppler shift frequency, and one at $\sim$ 80 kHz. We want to remove the component at 80 kHz. **And we'll do that with a Sallen-Key low-pass filter in this Lab 6**

2) Pre – Lab Design

The low-pass filter that we'll make in this system uses the Sallen-Key (S-K) topology. We would design the S-K low-pass filter (LPF) to meet some certain specifications.

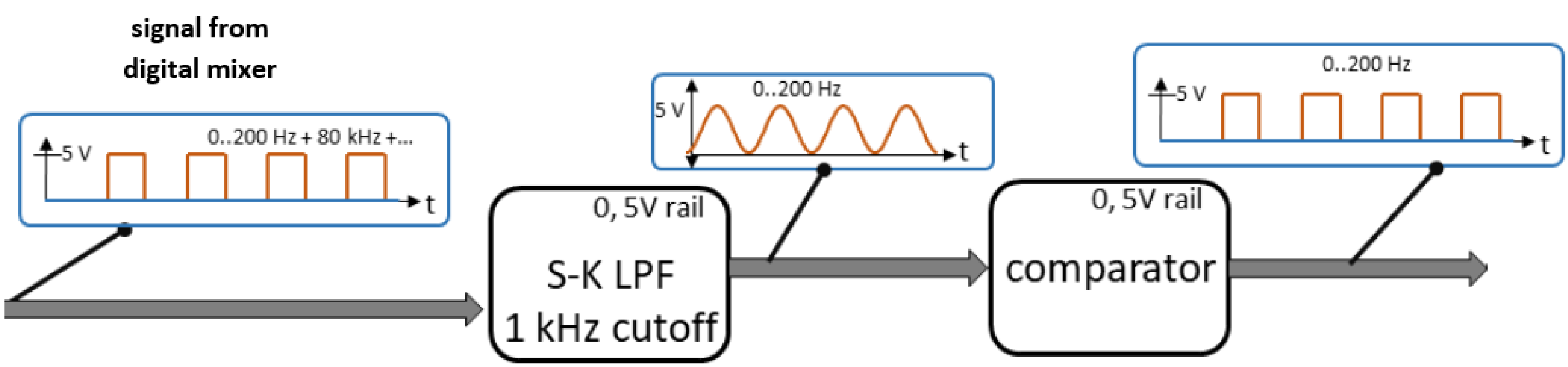
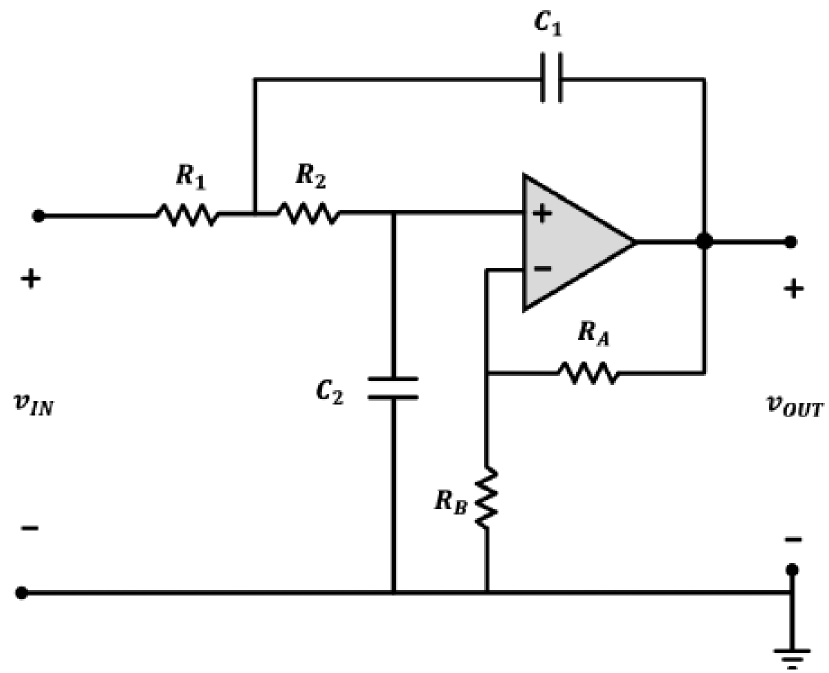


Figure 3:

Sallen-Key Low-Pass Filter



Checkoff 1:

- **Where is Figure 3 in the full schematic?**
- **Write down the values for R8, and R9 obtained from your design.**

In the S-K LPF schematic, there is a virtual ground of 2.5 V. However, we would ignore this (i.e. tie C2 to ground) when analyzing its circuit diagram shown in Figure 3 **(WHY?)**. Determine the following:

a) DC gain. *Note: at DC the two capacitors are open-circuits and thus drop out, then you can use typical op-amp analysis*

b) Voltage transfer function H(ω) i.e. $H(\omega) = \frac{V_{OUT}}{V_{IN}}$

c) Write the steady-state AC gain, and how do you obtain the DC gain from the expression obtained in b).

d) Let R1=R2=R and C1=C2=C, determine the cut-off frequency f_c and bandwidth. Sketch the plot of H(ω).

e) Choose R and C such that

- DC gain of 1 (~0 dB)
- Have the cutoff frequency be at 1kHz
- A -40dB/decade rolloff above the cutoff frequency
- Resistors ≥ 5 kΩ to minimize currents

3) Lab Preliminaries

Before starting this lab, make sure you have successfully finished the S-K LPF design problem in pre-Lab section.

4) Lab 6 Overview

See section 1. You'll recall from Lab 5, that we created a signal with two main frequency components, one at δf, the Doppler shift frequency, and one at ~ 80 kHz. We want to remove the component at 80 kHz. **And we'll do that with a Sallen-Key low-pass filter in this Lab 6. In addition, we include a second comparator in order to digitize our signal** into a nice square wave before sending it back to the Teensy.

5) Sallen-Key Low-Pass Filter (S-K LPF)

Take a look at the full system schematic to see where S-K LPF fit in, and populate the PCB accordingly. We will use a TLV2371 op-amp to build our Sallen-Key filter. You can find the pinout of this op-amp in Section 4 of Lab 4.

6) Second Comparator

Populate the PCB with the MAX 771 comparator and two resistors (R12=10 kΩ, R13=10 kΩ).

7) Let's Test It!

We will perform one primary test on our actual system, an end-to-end test: Power your board with 5 V and 30 V (and GND, of course) as before. As done in the previous lab, the 5V and the square wave is obtained using a teensy Arduino on a breadboard, powered by a USB connection to the laptop. Use same Arduino code of the previous lab, “PWM_code”. Ensure that you connect the two grounds from the 5 V and 30 V outputs to the ground test points on the board (TP10-TP13). Set up a reflector about a foot in front of your ultrasound transducers.

- Apply a square wave of 3.3 Vpp with 1.65 V offset at 40 kHz to TP1. Scope TP6, which is the output of the XNOR (or the digital multiplier). This should look like a square wave with two frequencies (~ 80 kHz and δf).
- Add a second scope probe at TP7, which is the output of the S-K low-pass filter.
- You should also see that a signal arises at TP7 when the reflector moves. This is the wave at the Doppler frequency!