CALIFORNIA STATE UNIVERSITY
LONG BEACH

Control Systems Laboratory
EE 370L
Fall 2019
v1.3

# Lab #5

## Op-amp systems

prepared by
Hossein Jula Ph.D.
Arya Daroui

## 1. Introduction

Operational amplifiers (op-amps) are one of the most ubiquitous components used in electronic circuits, especially the 741 IC. They are commonly used in analog control system design because their differential input and high gain make it trivial to implement feedback systems. In this lab, we will explore different op-amp systems, their behavior, and how to use these systems to learn more about modeling and designing control systems.

## 2. Procedure

We can use an inverting op-amp circuit, shown in Figure 1, as a subsystem to create larger systems. By choosing $Z_a$ and $Z_b$,

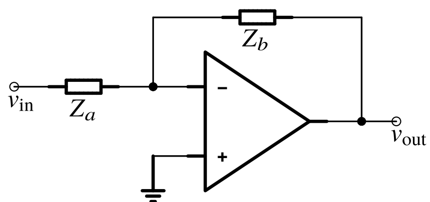


**Figure 1.** Inverting op-amp circuit where $v_{\text{out}} = -v_{\text{in}} \frac{Z_b}{Z_a}$

we can implement different transfer functions for the circuit. Consider the arrangements $Z_0$ to $Z_3$ below in Figure 2.

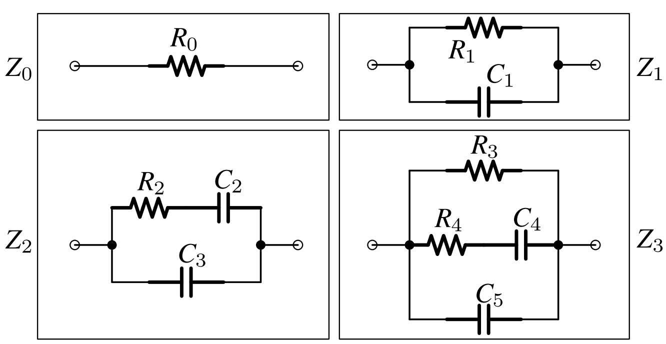


**Figure 2.** Impedance subcircuits

These impedance subcircuits correspond to the equations

$$Z_0 = R_0 + 0j$$

$$Z_1 = \cfrac{1}{\cfrac{1}{R_1} + j\omega C_1}$$

$$Z_2 = \cfrac{1}{\cfrac{1}{R_2 + \cfrac{1}{j\omega C_2}} + j\omega C_3}$$

$$Z_3 = \cfrac{1}{\cfrac{1}{R_3} + \cfrac{1}{R_4 + \cfrac{1}{j\omega C_4}} + j\omega C_5}$$

### 2.1 First order system

Create a simple first order circuit by choosing the impedances

$$\begin{aligned} Z_a &= Z_0 \text{ where } R_0 = 50\ \text{k}\Omega \\ Z_b &= Z_1 \text{ where } R_1 = 50\ \text{k}\Omega \\ C_1 &= 10\ \mu\text{F} \end{aligned}$$

This yields the transfer function

$$G_1(s) = \frac{-2}{s+2} \tag{1}$$

Find the step response of this system by inputting a square wave into your circuit. Visualize the output on your myDAQ oscilloscope and export it. Make sure you set the period of the wave to be long enough that the output can reach steady state.

### 2.2 Cascading

We can create a cascaded system by feeding the output of one subsytem into the input of the next. Do this by using (1) for both subsystems to create the overall system $H_{11}$. Find the transfer function of $H_{11}$, visualize the step response on your myDAQ oscilloscope, and export the scope data.

### 2.3 Cascading with negative feedback

In the inverting op-amp circuit in Figure 1, the output is tied to the negative terminal of the op-amp, creating a negative feedback loop where the gain of the system depends upon the ratio between the feedback impedance $Z_b$ and the input $Z_a$. Similarly, we can also tie the output of the cascaded system back to the negative terminal of the first op-amp. Multiple voltage inputs into a single op-amp is called an op-amp adder, functioning as a summing junction for our signals. To test this, add a negative feedback loop to the cascaded system from the previous subsection as shown in Figure 3.

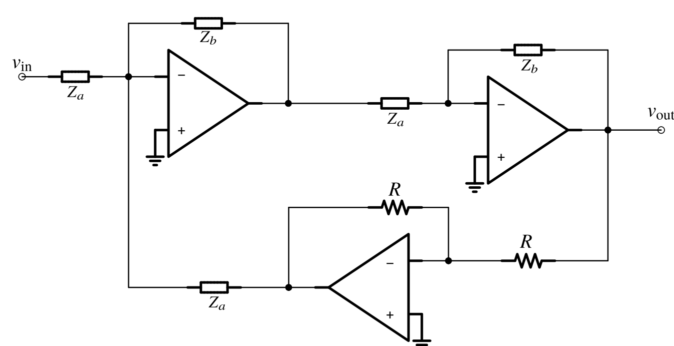


**Figure 3.** Cascaded, negative feedback op-amp adder circuit

Notice the inverting buffer in the feedback loop with some positive resistance $R$. Find the transfer function of the system, visualize the step response on your myDAQ oscilloscope, and export the scope data.

## 2.4 Modeling

Using MATLAB/Simulink, model the first order system, the cascaded system, and the cascaded feedback system with the transfer functions you found and the one that was given. Compare the results of the model with the actual data.

## 2.5 Dominant pole approximation

A higher order system's response can be approximated by a lower order system if the higher order system has poles sufficiently far enough (usually at least five times farther) from its dominant poles. In which case, a lower order system with poles equivalent to the dominant poles can be considered a reasonable approximation.

### 2.5.1 Lower order system

Find the poles of cascaded system $H_{11}$ in §2.2.

### 2.5.2 Higher order system

Now we want to cascade $H_{11}$ with a different function with poles sufficiently far away. Create another op-amp system with impedances

$$\begin{aligned} Z_a &= Z_0 \text{ where } R_0 = 1\ \text{k}\Omega \\ Z_b &= Z_3 \text{ where } R_3 = 1\ \text{k}\Omega \\ R_4 &= 10\ \text{k}\Omega \\ C_4 &= 1\ \mu\text{F} \\ C_5 &= 1\ \mu\text{F} \end{aligned}$$

This gives the transfer function

$$H_2(s) = \frac{-1000s - 100000}{s^2 + 1200s + 100000} \tag{2}$$

Cascade $H_{11}$ and $H_2$ together create the overall system $H_{112}$. Find the transfer function of $H_{112}$ along with its poles. Visualize the step response on your myDAQ oscilloscope and export it. Compare the responses of $H_{11}$ and $H_{112}$.

# 3. Report deliverables

For §2.1:

- Plot of the system

For §2.2:

- Plot of the system
- Equation of the system

For §2.3:

- Plot of the system
- Equation of the system

For §2.4:

- Block diagrams of systems
- Plots of the actual system response compared with the modeled response
- Quantitative comparison of the model and the actual response

For §2.5:

- Transfer functions of both cascaded systems
- Poles of both cascaded systems
- Step response of both cascaded systems