



Santa Clara

U N I V E R S I T Y

MECH 160: Lab Four: Thermoelectric Control

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Abstract:

Introduction:

This lab focused on developing a PID control system to regulate the temperature of a Peltier tile (thermoelectric apparatus) using a thermocouple, an NI 9174 Compact DAQ with appropriate modules, and a reversible power supply. The thermoelectric apparatus also had a fan attached to the bottom of the chip, which needed a separate 5V power supply. The thermocouple, along with some thermal paste, was inserted into a block of aluminum attached to the hot side of the Peltier tile.

The in-lab portion was separated into two different parts: the first one to correctly calibrate the sensors, record some data, and the second to compete in a control competition to go from 22°C to $16^{\circ}\text{C} \pm 0.1$. Using our knowledge of PID controllers, we could change the gains to control the voltage sent to the Peltier tile, which, in turn, regulates the temperature. The quickest time to achieve the steady state value of 16°C would win.

Experimental Setup:

The first step of the lab was to correctly set up the circuit, block diagram, and ensure that all other devices were functional. Most of the prep work was done in the prelab, and all that had to be finished during the lab was the LabVIEW itself. The assembly was made up of the heating assembly and the control assembly, which included the DAQ.

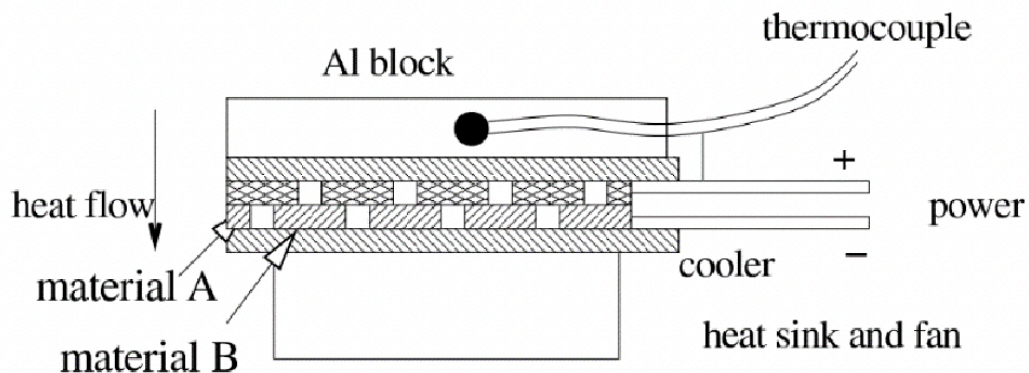


Figure 1: Heating Assembly

The controller assembly was made up of the NI 9174 Compact DAQ with modules 9263 and 9213, along with the reversible power supply, which was controlled with LabVIEW. The LabVIEW followed the setup outlined by the prelab and used the DAQ assistant module as well as a loop.

Procedure:

The measurement and control system was put together to start the experiment by connecting the reversible DC power supply to the NI-9263 voltage output module and wiring the Type-K thermocouples into the NI-9213 input module. Figure 1 below shows the LabVIEW block diagram, which was created to provide a regulated voltage signal that stayed within the range of -3.00 V to 3.00 V and to read the temperature outputted by the thermocouple.

INSERT LabVIEW SCREENSHOT HERE

Figure 2: LabVIEW Block Diagram used for System Control

Initial testing was done to verify that the voltage output and thermocouple were functioning as needed. The fan's thermal response was observed, and sources of noise or other non-ideal behavior were found by applying small input voltages to the system. Live graphs were used in LabVIEW to visualize the testing.

After confirming that the sensor and actuation components were working properly, the system's heat transfer performance was tested. The net heat absorbed during cooling was calculated using the thermal mass of the aluminum block, and the ideal and real coefficients of performance were calculated by looking at the temperature versus time data. The system's efficiency was estimated by measuring the temperature gradient between the two aluminum blocks using a second thermocouple.

After establishing the open-loop behavior, a PID block was added to the LabVIEW block diagram so that closed-loop control could be implemented. The thermocouple signal was input into the PID controller, and the controls for the temperature and PID gains were added. Initially, gains were tuned to achieve an underdamped, overdamped, and critically damped response. After observing the three to better understand the effects of each gain value, the Ziegler-Nichols method was used to get rough values for the gain. Once a satisfactory response was achieved, trial and error based on the fundamental PID equation was used to dial in the values. The effects of the changes on settling time and overshoot were observed, with any values overshooting past the steady state being thrown out immediately. The gains were tuned to cool the system from 22°C to the 16°C target while staying within the $\pm 0.1^\circ\text{C}$ tolerance for steady-state as quickly as possible.

Results:

DC Power Supply Gain

Input Voltage (V)	Output Voltage (V)	Gain
0.5	0.745	1.490
1	1.49	1.490
2	2.94	1.470
3	4.42	1.473
2.5	3.68	1.472
2.75	4.05	1.472

Cooler Test

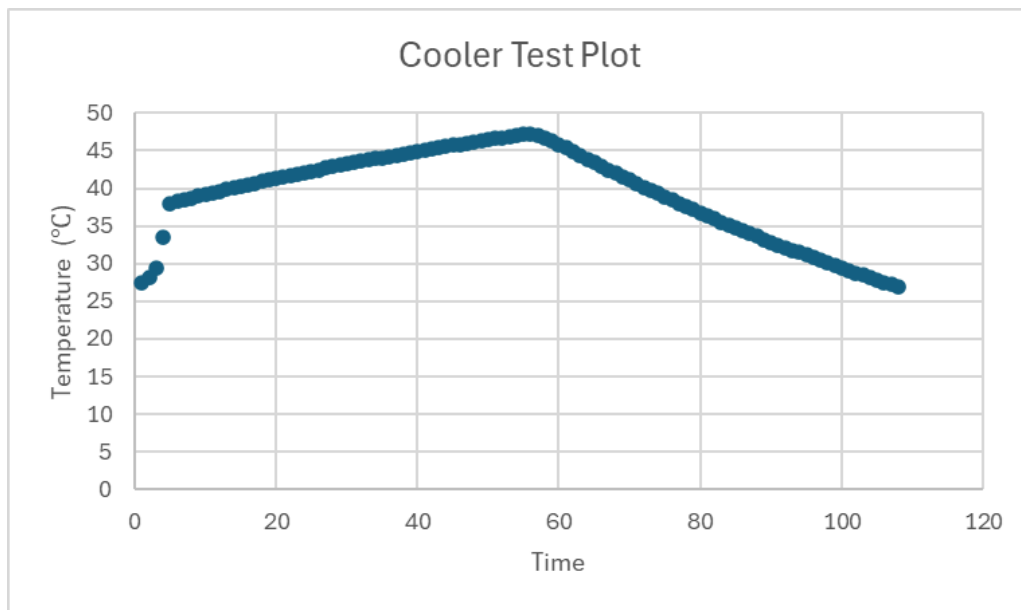


Fig #. Cooler test plot 2,-2 voltage Input

A possible error source for the cooling system is that the cooling system relies on the ambient air to help cool the blocks. Therefore, it is important to keep the ambient temperature relatively constant and ensure other possible heat sources, like a power supply, are not interfering with the results.

Heat Transfer and COP

Method A:

Transient Cooling - Temperature vs. Time

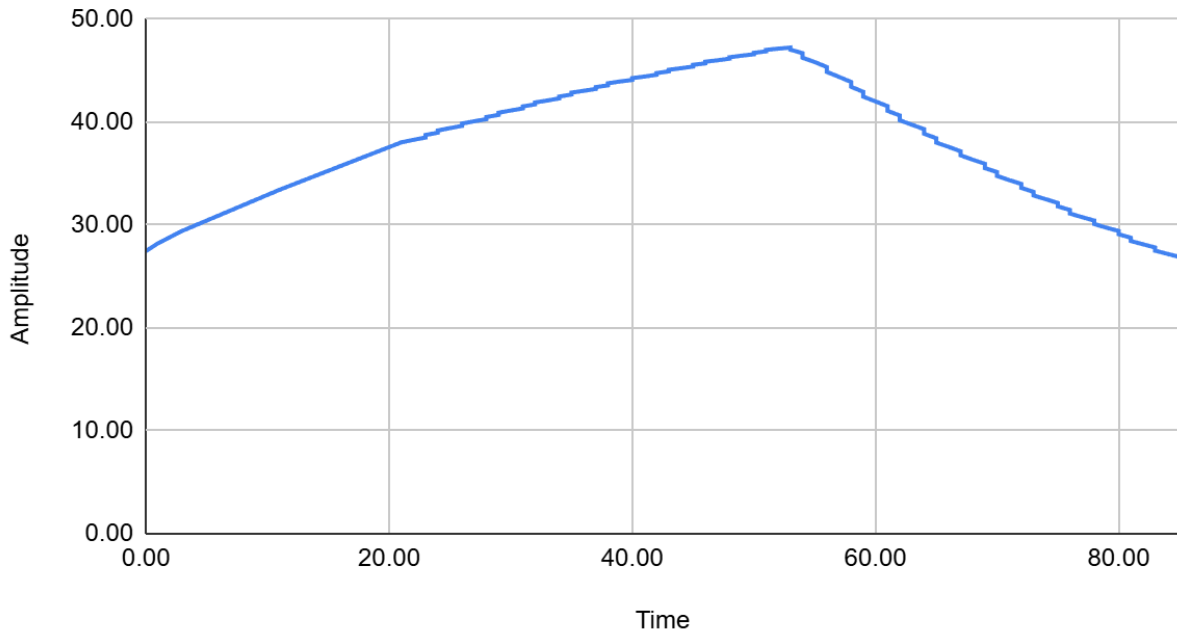


Figure #: Aluminum Block Temperature vs. Time During Transient Cooling

Amplitude vs. Time (Linear Fit)

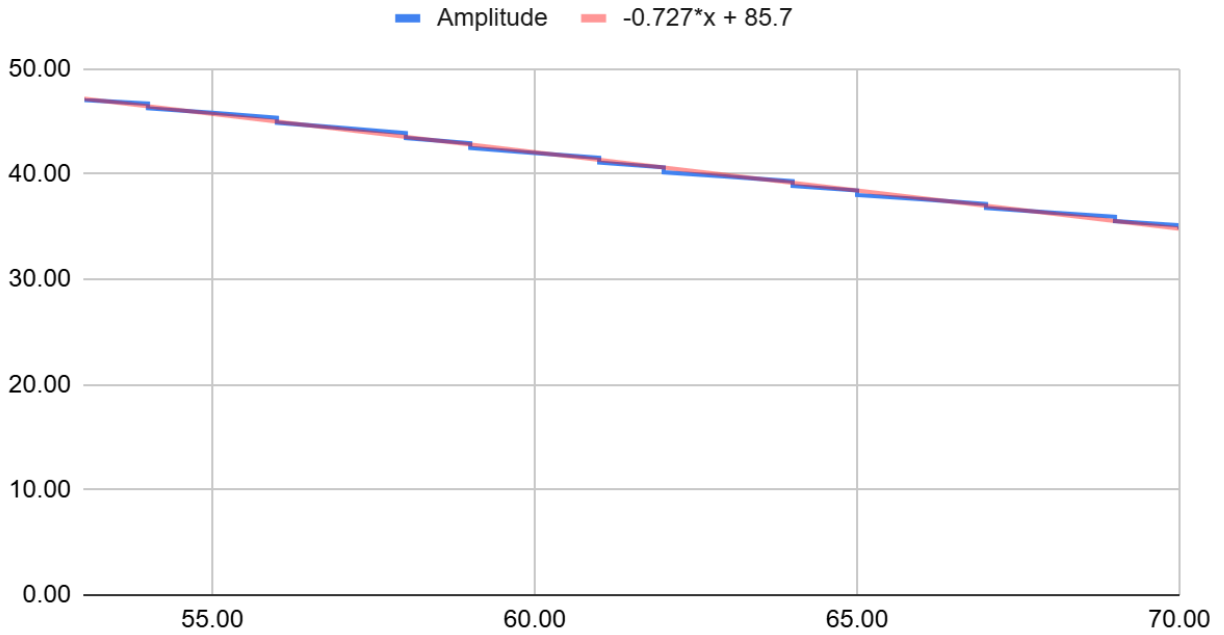


Figure #: Aluminum Block Temperature vs. Time During Transient Cooling with Linear Fit

- Mass: $m_{Al} = 17.74g$
- Specific heat: $c_{Al} = 900 J/kg \cdot K$
- Slope from linear fit: $\frac{dT}{dt} = - 0.727 K/s$

$$Q = c_{Al} \cdot m_{Al} \cdot \frac{dT}{dt} = (900 J/kg \cdot K) \cdot (0.01774 kg) \cdot (- 0.727 K/s) = - 11.61 W$$

The cooling heat transfer rate was approximately 11.6 W

- Voltage: $V_{in} = 3.0 V$
- Current: $I_{in} = 1.4 A$ (Approximated from chart)

$$P = V_{in} I_{in} = (3.0 V) \cdot (1.4 A) = 4.2 W$$

$$COP = \frac{Q}{P} = \frac{11.6 W}{4.2 W} = 2.76$$

Method B:

Top vs. Bottom Temperature

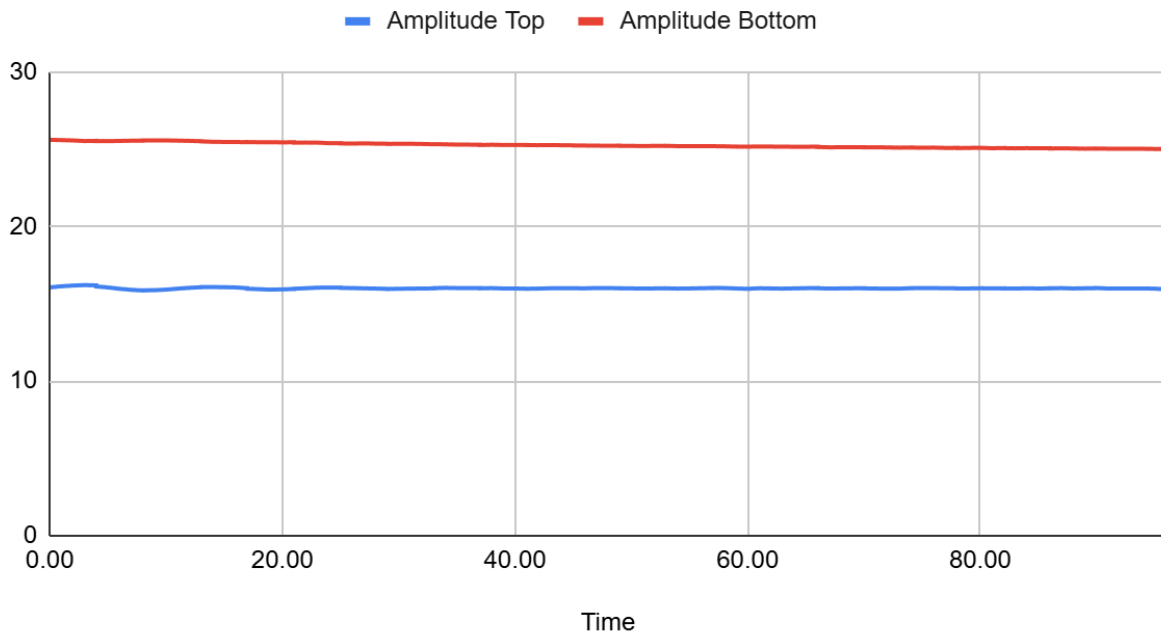


Figure #: Top and Bottom Block Temperatures vs. Time at Steady State

Averages from plots:

- $T_c = 16.00 \text{ }^\circ\text{C}$
- $T_h = 25.26 \text{ }^\circ\text{C}$

Other information:

- $A = 9.0 \times 10^{-4} \text{ m}^2$
- $L_{TEM} = 4.70 \text{ mm} = 4.70 \times 10^{-3} \text{ m}$
- $L_{Al} = 7.30 \text{ mm} = 7.30 \times 10^{-3} \text{ m}$
- $k_{TEM} = 10 \text{ W/m} \cdot \text{K}$
- $k_{Al} = 205 \text{ W/m} \cdot \text{K}$

$$\Psi_{TEM} = \frac{L_{TEM}}{k_{TEM}A} = \frac{4.70 \times 10^{-3} \text{ m}}{(10 \text{ W/m} \cdot \text{K})(9.0 \times 10^{-4} \text{ m}^2)} = 3.96 \times 10^{-2} \text{ K/W}$$

$$\Psi_{Al} = \frac{L_{Al}}{k_{Al}A} = \frac{7.30 \times 10^{-3} \text{ m}}{(205 \text{ W/m} \cdot \text{K})(9.0 \times 10^{-4} \text{ m}^2)} = 5.22 \times 10^{-1} \text{ K/W}$$

$$\Psi_{Tot} = \Psi_{TEM} + 2\Psi_{Al} = (3.96 \times 10^{-2} \text{ K/W}) + 2(5.22 \times 10^{-1} \text{ K/W}) = 0.601 \text{ K/W}$$

$$Q = \frac{T_h - T_c}{\Psi_{Tot}} = \frac{(25.26 \text{ }^\circ\text{C}) - (16.00 \text{ }^\circ\text{C})}{0.601 \text{ K/W}} = 15.4 \text{ W}$$

$$P_{in} = Q_J = 4.2 \text{ W}$$

$$Q = Q_C + Q_J \rightarrow 15.4 \text{ W} = Q_C + 4.2 \text{ W} \rightarrow Q_C = 11.2 \text{ W}$$

$$COP = \frac{Q}{P_{in}} = \frac{11.2 \text{ W}}{4.2 \text{ W}} = 2.67$$

Efficiency:

$$COP_{Ideal} = \frac{T_c}{T_h - T_c} = \frac{289.15 \text{ K}}{298.41 \text{ K} - 289.15 \text{ K}} = 31.2$$

$$\eta = \frac{COP_{Real}}{COP_{Ideal}} = \frac{2.67}{31.2} = 0.085 = 8.5\%$$

The differences in the coefficients of performance were very similar between the two methods with a difference of only 0.09. This demonstrates that we tested on a consistent system with inconsistencies likely

Thermal Efficiency

Thermal Mass 15.97g

$$P = VI$$

$$Q = Q_c + Q_J$$

$$\mu = \frac{Q_c}{P}$$

$P = 2V * 3amps$ (estimated from datasheet)

$P = 6 watts$

$$Q = Q_c + Q_j$$

$$\mu = \frac{Q_c}{P}$$

$$\mu = \frac{Q_c}{6}$$

PID Gain Response

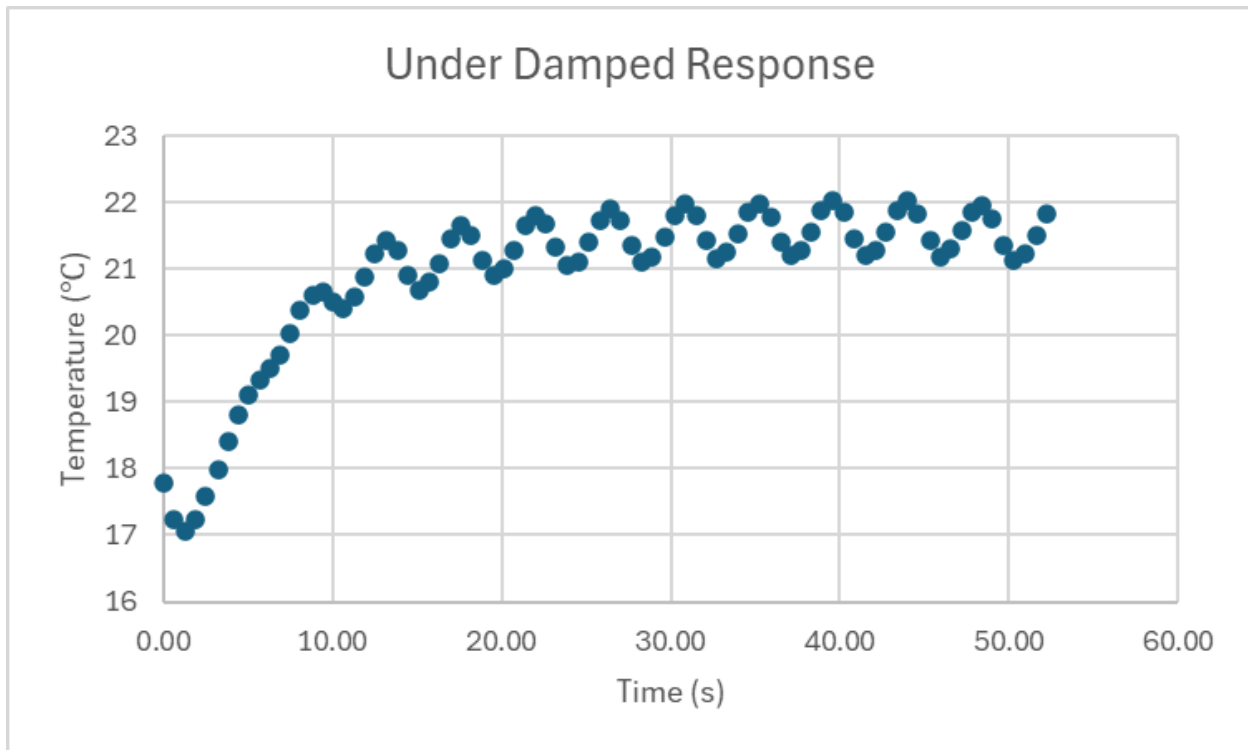


Fig #. Under-damped Response plot (P=10.94, I=0.109 D=0.003)

An underdamped response is caused when the proportional gain is much higher than the Integral gain, such that the integral gain cannot “overcome” the proportional gain when approaching the set point. To fix this, the proportional gain can be decreased, which will slow response time but prevent oscillation.

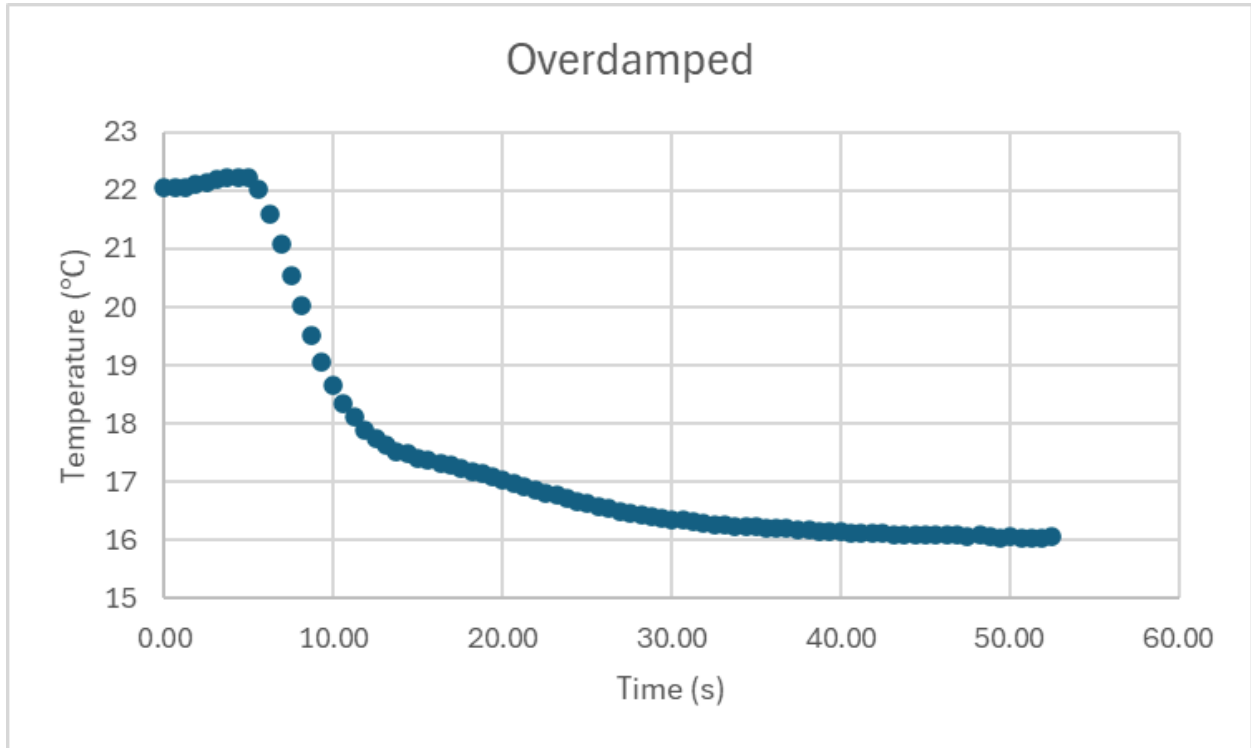


Fig #. Under damped Response plot (P=1,I=2,D=0)

An overdamped response is caused when the Integral gain is much higher than the proportional gain, and therefore it starts slowing well before reaching the set point and takes much longer to reach it. To fix this, the proportional gain can be increased to quicken the response, but too large an increase could result in an underdamped response.

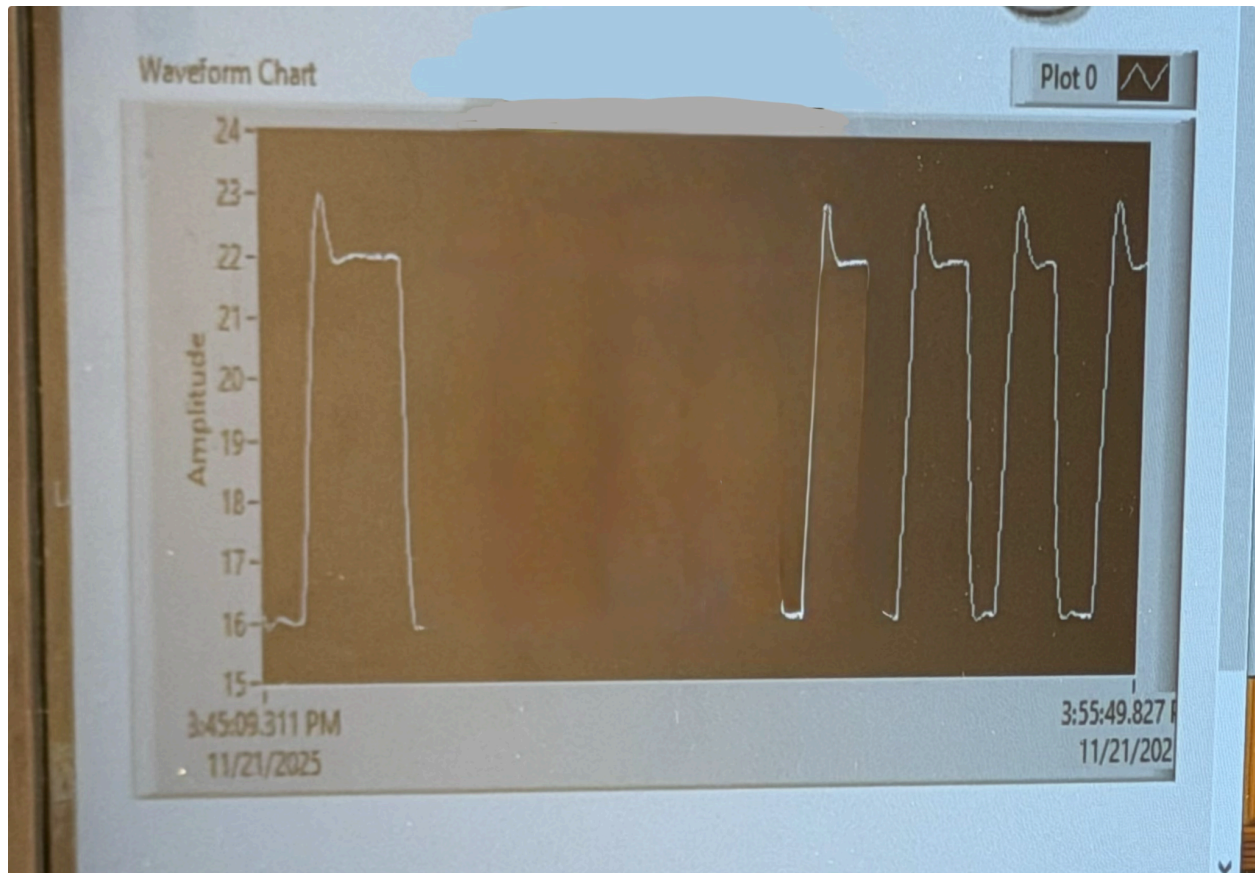


Fig #. Optimised Response plot ($P=0.94$, $I=0.107$, $D=0.0030$)

For an optimised response, it is important to have a balance of all three gains. Proportional gain is important for a quick response time, Integral gain is important for an accurate steady state, and Derivative gain is important for controlling overshoot. The Final values settled on were $P=0.94$, $I=0.107$, $D=0.0030$. These values were able to drop the temperature from 22 to 26 degrees in less than 14 seconds, and hold an accurate steady state for 30 seconds.

Analysis:

For the competition portion of the lab report, we started by using the Ziegler–Nichols method to find the proper gain values. However, this quickly devolved into simply guessing the gains. The PID controller that was used in the lab used a different method than what the lecture taught. Proportional gain instead affected both the Integral gain as well as the Derivative gain, acting as a factor for the Derivative gain and as a denominator for the Integral gain.

The major focus of the lab group was to eliminate the overshoot: the Peltier tile received maximum voltage during the first slope of the signal, and the voltage quickly dropped off after it crossed into the desired temperature region. Using this method, a time of around 14 seconds was achieved, while at the same time, the rest of the groups hadn't broken the 30-second mark.

The best time that was recorded unofficially was around 12 seconds; however, we were unable to reproduce this value in a timed capacity. The setup itself was very prone to outside factors, such as a breeze from someone walking past, a shift to where the thermocouple was placed, or the USB plug connecting the DAQ being jostled. Additionally, LabVIEW's decimal limit on the indicators would round to the nearest integer, which meant that, hypothetically, a group could start the starting temperature at 21.5°C and still make it look like 22°C.

Conclusion:

This lab established baseline thermal properties, including cooling capacity, COP, and overall heat transfer rate. The measurements we took proved that the system behaved as a nonlinear process, especially in the differences in heating and cooling of the tile itself. Once we added a closed loop, we could observe the effects of the PID controller on the temperature. As we expected, the higher Proportional gains were necessary for our quick time; however, the true balancing of the gains was made apparent during our attempts to rectify the overshoot and inaccuracies of a higher Proportional gain. We started by using the Ziegler–Nichols tuning method, but had much more success by guessing the numbers ourselves and getting a feel of how the temperature curve would react. Our recorded optimized gains of $P = 0.94$, $I = 0.107$, $D = 0.0030$ allowed our system to reach a steady state temperature of 16°C within 14 seconds, which was noticeably faster than other groups at that time. We did, however, notice how sensitive the system was to outside influences, as many times, we would retest a set of gains and arrive at different times each time. The lab used concepts from MECH 142, and together with LabVIEW gave us a strong understanding of PID controller tuning.

References: