ME 3300 Lab-08: Thermocouple - Step Response

Dr. Christopher Bitikofer

Contents

1 Learning objective

The objectives of this experiment are to provide the student with an opportunity to:

1. Learn how to use a thermocouple to measure temperatures
2. Estimate the time constant of a thermocouple based on its step input response using two different methods
    - Using error fraction method
    - Using time required to reach 62.3% of the final response

2 Required Equipment

1. AD595AQ Thermocouple Instrumentation Amplifier
2. K-Type Thermocouple
3. LM358 Op-Amp
4. Powered breadboard
5. Digital Multi-meter
6. Wire kit and resistor kits
7. Screwdriver, pliers, wire stripper
8. Hot plate, beaker, stirrer, stands, and clamps
9. Liquid-In-Glass Thermometer (LIGT)

3 Introduction

In many applications, it is necessary to make measurements of a quantity that is rapidly changing with time. In order to do this, we have to know how the measurement system being used will respond to such dynamic inputs. The ability of a measurement system to respond to a time-varying input is called its dynamic response. We will be studying a thermocouple, which can be modeled as a first-order system.

First-order dynamic response is characterized by one parameter, τ, the time constant. The physical meaning of a temperature device's time constant is most easily seen when it is exposed to a step change in temperature. In this case, the time constant describes the time required for the indicated temperature of the device to change 63.2% of the way from its initial to the final temperature. The time constant of a temperature-measuring device will be a function of the device's physical properties and the heat transfer characteristics of the measured medium.

4 Laboratory instruction

This experiment Analog Device's "AD595AQ" Monolithic Thermocouple Amplifier with Cold Junction Compensation" (see appendix 6). This 14-pin chip combines an ice point reference with a pre-calibrated amplifier to produce a high-level voltage (10mV/C) output directly from a K-Type (chromel-alumel) thermocouple. Because the output from the AD595AQ has low impedance, we will buffer the output from the AD595AQ from the input to the NI-MyDAQ USB data acquisition device using a voltage follower circuit.

A voltage follower or buffer amplifier circuit is commonly used to isolate the impedance load from other stages of the circuit or measurement system. In this experiment, it will be used to provide the same voltage output from the thermocouple amplifier to the data acquisition system. A voltage follower circuit is shown in Fig. 1. For the op-amp pins and circuit, refer to the experiment with op-amp.

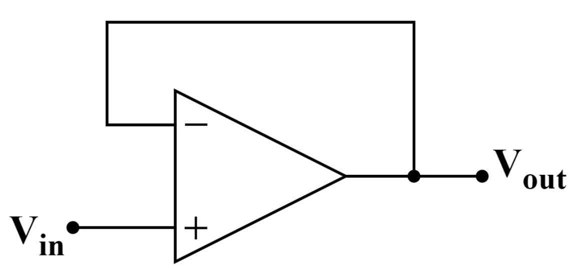

Figure 1: A typical voltage follower circuit

4.1 Part 1: Experimental Circuit Setup

1. Set up a heated water bath as shown in Fig. 2.
2. Identify any safety issues with the use of water and electrical components, as well as boiling water.
   - Avoid touching the beaker and the hot plate.
   - If you need to move it, ask a TA to move it for you.
3. Place the stirrer into the beaker and it reaches a higher speed.
4. Make sure that the liquid-in-glass thermometer is at the appropriate calibration depth.
5. At the beginning of the lab, increase the heating of the water immediately to save time.
6. Once the water is boiling, reduce the heat to a simmer.
   - Set the stirrer to a low setting.
7. Construct the circuit shown in Fig 3. using the AD595AQ thermocouple chip and the LM358 Op-Amp. Use the powered breadboard to make it easier to integrate it with the voltage follower circuit.
8. Notes for AD565Q connection:
   - +5V from DC power supply is supplied to Pin 11
   - Supply voltages to the LM358 Op-Amp are +15V and -15V
   - Pins 1, 4, 7, and 13 on the AD595AQ are connected to the common ground
   - The voltage out of the AD595AQ (Pin 9) is the input of the voltage follower circuit (Pin 3).
   - Pins 1 and 14 on the AD595AQ are connected to the thermocouple.
9. When data collection is running, hold the thermocouple wire in a constant location in the heated bath.
10. Make sure that the thermocouple is not touching the beaker, as it may produce inaccurate measurements.

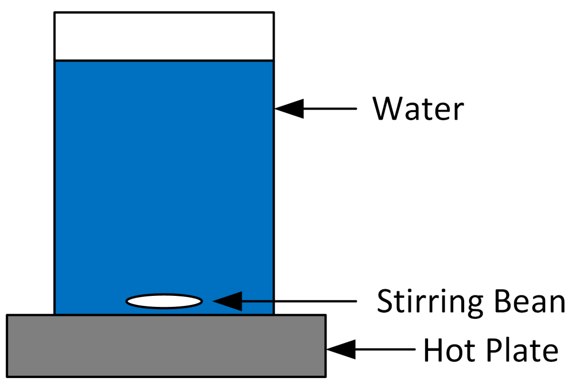

Figure 2: Heat bath for thermocouple experiment.

4.2 Part 2: Thermocouple calibration (2-point calibration)

1. Update the code **MATLAB_Data_Acquisition.m** to match the provided code on Canvas and with the following settings.
   - Reference **MATLAB_Data_Acquisition.m** from lab 2.
2. Collect the single-channel voltage output from ([0]).
   - Duration: 10 seconds
   - Sample rate: 50 samples per second
   - Leave the slope = 1 and bias = 0.
3. Leave the LIGT away from the hot plate and beaker.
4. Record the thermocouple measurement (volts) and the LIGT measurement of the ambient air temperature.

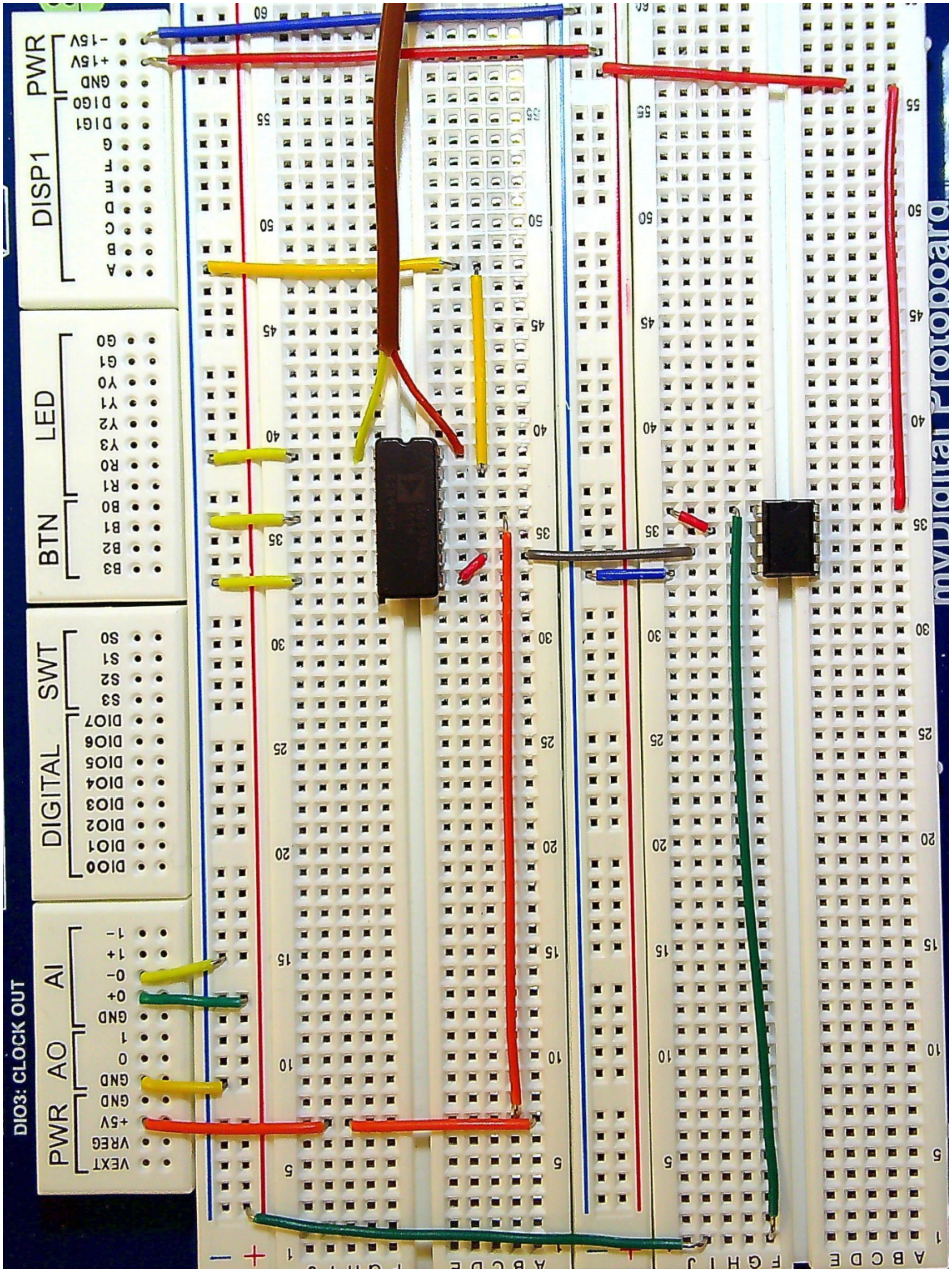

Figure 3: Sample circuit for the thermocouple chip and voltage follower circuit.

   - Note the unit of temperature used.
5. Hang the LIGT from the laboratory stand in the slow-boiling water (with the stirrer on low).
6. Record the thermocouple measurement and the LIGT measurement of the slow boiling water.
   - Note the unit of temperature used.
7. Remove the thermocouple from the heated bath and allow it to return to room temperature.

8. Use the two data points and perform linear regression analysis calibrate the thermocouple measurement system.

Q: How accurate is the sensitivity and bias of the AD595AQ? Is the two-point calibration enough?

4.3 Part 3: Thermocouple Step Response

1. On your **MATLAB_Data_Acquisition.m** code, change the slope and intercept values acquired from the calibration step (part 2).
   - Reference **MATLAB_Data_Acquisition.m** from lab 2.
   - Check your code:
     - Measure room temperature and it should match the LIGT temperature.
     - The modified Matlab program should output temperature rather than the volts.
     - Measure heat bath temperature and it should match the LIGT temperature.
2. Collect the single-channel voltage output from ([0]).
   - Duration: 5 seconds
   - Sample rate: 1000 samples per second
   - Leave the slope = 1 and bias = 0.
3. For the main experiment, high sample rate is necessary because you will be capturing the dynamic response of the thermocouple.
4. Steps for the main experiment:
   - Keep thermocouple tip a few inches away from the beaker.
   - Start the data acquisition program.
   - Once the figure pops up, immediately (but safely) plunge the thermocouple into the heated bath.
   - Save a data file using this naming convention: **Plunge_XX.csv** where
     - `XX` indicates the current dynamic measurement.
   - Update the file name before each run to avoid overwriting data.
   - Repeat for three successful runs. (review "List of common mistakes" to determine success of the run)
   - Ensure that the thermocouple reaches room temperature before repeating the steps.
5. Record the heated bath temperature of the LIGT for each run in your log book.
6. List of common mistakes:
   - Gage the success of the experiment by observing the output plot.
   - The plot should follow the exponential curve as seen in Fig.4.
   - Mistake 1: the exponential curve has an initial bump caused by the steam coming from the boiling water.
     - Resolution: ask TA to add more water to your beaker.
   - Mistake 2: the exponential curve is bump causes by the thermocouple not being at a proper depth.
     - Resolution: ask TA to add more water to your beaker.
     - Resolution: Bring the circuit a little close to the beaker.
   - Mistake 3: Initial temperature is way above room temperature.
     - Resolution: let thermocouple cool off before repeating experiment.
   - If success is not apparent, repeat the above steps.
7. Save your data for use in the Post-Laboratory report.
8. For each of these experimental data sets, plot the raw temperature vs. time, with the following steps:
   - Identify the start time of the step input(when the thermocouple entered the boiling water, not the steam).

- Open variable with time and temperature.
- Use the list of temperatures to find the proper index and find the matching time.

- Plot all 3 on a single graph, with the time adjusted so that all 3 dynamic responses begin at $t = 0$.
- Set your x-axis limits to show a small portion of the data before the plunge and the transient responses until the convergence is clear (do not plot the full time of recording).

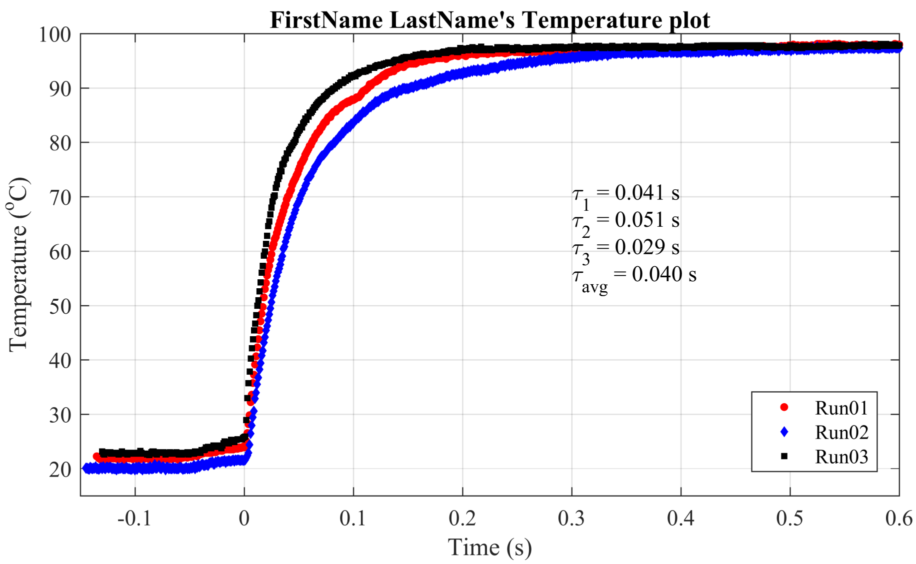

Figure 4: Step response plot of thermocouple for different test runs

4.4 Part 4: Time constant analysis-method-01

Here we will perform the time-constant calculation using the two different approaches. The first approach will utilize the time required to reach 63.2% of the steady state value, and the second approach will use the error fraction method.

1. Plot the temperature vs time data (all three runs).
2. Ensure that at t=0s the temperature of the thermocouple starts to rise. (Talk to TAs; if you are not sure of the steps)
   - The current method depends on whether t=0s being correct to implement correctly.
   - Find the temperature at t=0s (T_o).
   - Find the temperature at the steady state (T_{ss}).
   - Open csv folder, "data" variable, or figure of data to find these values.
3. Use the following equation to find temperature needed to reach 63.2% of the steady:

$$T(\tau) = T_o + 0.632(T_{ss} - T_o) \tag{1}$$

4. Identify the time required to reach 63.2% of the steady state value. Here you may have to zoom in to get accurate value of time constant.
5. Complete this for the three data sets.

4.5 Part 4: Time constant analysis-method-02

Select one of your best data sets for time constant estimation using error fraction method. Here you have to modify the Matlab code submitted during the prelab assignment.

1. Modify the code provided, **MATLAB_time_constant_method_02.m**, to calculate the error fraction (Γ) and plot the natural log of Γ as a function of time.
2. For calculating Γ you have to identify the initial temperature (T_o) and (T_{ss}).
   - Find index value of the (T_o) and (T_{ss}).

- Make sure to reference the T_{ss} value from the LIGT.

3. For this analysis you have to only use range of data set that shows exponential trend.
    - With the found index, modify the Matlab program with the index values of the (T_o) and (T_{ss}).
    - Afterward, reduce the index for (T_{ss}) so that you appropriate range of data.
    - Talk to TAs' about this if you are confused.
4. Perform linear regression analysis to determine the slope of the line (Hint: $\ln(\Gamma)$ as the dependent variable and t as the independent variable).
5. Plot $ln(\Gamma)$ vs. time and the resulting curve fit (from linear regression analysis).
6. Time constant is given as $\tau = -1/\text{Slope}$

Q: Compare time constant using this method to the time constant calculated form Method-1. Do they match? Why? Why not? **Q:** What is the impact of selecting different range of data for this analysis?

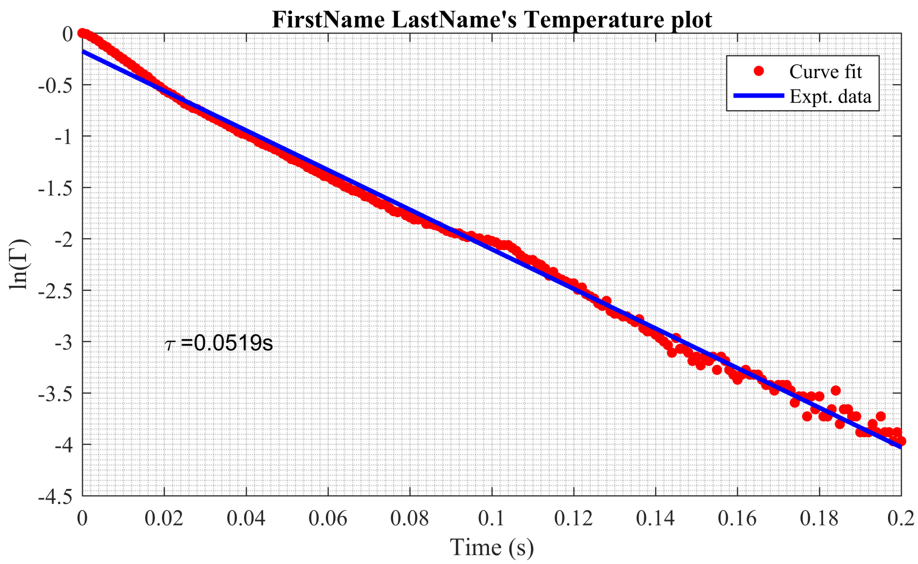

Figure 5: Sample error fraction plot for one test runs.

Equation showing the relationship between Γ and the time constant (τ).

$$
\begin{aligned}
ln\Gamma &= -\frac{1}{\tau}t \\
ln\left(\frac{T(t) - T_{ss}}{T_o - T_{ss}}\right) &= -\frac{1}{\tau}t
\end{aligned}
$$

5 Post-Laboratory

For this experiment, submit the following items on Canvas for your post-laboratory assignment.

1. **Step response plot of thermocouple for different test runs**
    - Submit a single figure with temperature plotted(^oC) vs. time(seconds) for all three step responses.
    - The step response data should be time shifted so that the step time for all 3 occurs at $t = 0$.
    - The plot should focus on the transient response, and should include a small amount of data before the step input change.
        - Using "scatter" plot function, raw data points should be with `MarkerSize = 10`.
    - The plot should be 3.5" tall and 6.5" wide.
    - Properly annotate your plot: axis labels, title, legend, etc.

- Include legend of all different sampling types.
- Text should be included of the individual time constants and the averaged time constant.
  - Use title: "FirstName LastName's Temperature Plot".
- Set axis grid lines on, box off, and figure background color to white.

2. **Sample error fraction plot**
3. Thermocouple Step Response Plot.
   - Submit a single figure for one of the temperature plots with the natural logarithm of error fraction vs time.
   - Compare the time constant acquired using this method to the time constant acquired using the step response plot.
     - Using "scatter" plot function, raw data points should be with `MarkerSize = 10`.
   - The plot should be 3.5" tall and 6.5" wide.
   - Properly annotate your plot: axis labels, title, legend, etc.
   - Text should be included of the individual time constants.
     - Use title: "FirstName LastName's Error Fraction Plot".
   - Set axis grid lines on, box off, and figure background color to white.
4. Thermocouple Error Fraction Plot.
5. Answer all questions in the post-lab assessment on Canvas.

6 Appendix

6.1 AD594/AD595

The AD594/AD595 is a complete instrumentation amplifier and thermocouple cold junction compensator on a monolithic chip.It combines an ice point reference with a precalibrated amplifierto produce a high level (10 mV/^oC) output directly from a thermocouple signal. Pin-strapping options allow it to be used as alinear amplifier-compensator or as a switched output setpoint controller using either fixed or remote setpoint control. It can be used to amplify its compensation voltage directly, thereby converting it to a stand-alone Celsius transducer with a low impedance voltage output.The AD594/AD595 includes a thermocouple failure alarm that indicates if one or both thermocouple leads become open. The alarm output has a flexible format which includes TTL drive capability.The AD594/AD595 can be powered from a single ended supply(including +5 V) and by including a negative supply, temperatures below 0^oC can be measured. To minimize self-heating, an unloaded AD594/AD595 will typically operate with a total supply current 160 μA, but is also capable of delivering in excess of ±5 mA to a load. Detail information can be found at Sparkfun website. A general schematic of the AD595 is shown in figure 6.

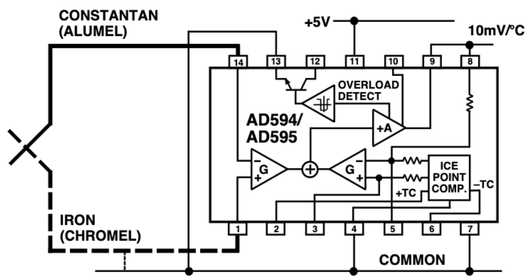

Figure 6: Schematic showing single supply operation.