ME 646 – Lab # 2

**Static and Dynamic Characteristics of Measurement Systems**

**Purpose:**

The first purpose of this laboratory exercise is to teach you techniques used to characterize the static and dynamic response of a thermal sensor. The sensor is expected to follow a first-order system response. You will analyze your results to determine the static sensitivity and the time constant. You will use statistical concepts to estimate the uncertainty of your results.

The second purpose of the laboratory exercise is to train you to present your results in an organized manner in the form of an internal report. These reports are intended to be useful to subsequent managers, employees and colleagues and are expected to be clear, informative, and well-documented.

The lab assignment is presented in two parts. The first part is acquisition and analysis of the data and the second part is writing the report. For the first part, you are required to submit the deliverables described at the end of this document one week after completing the measurements in the lab

The second part sets up the premise of the lab report by defining your audience. We provide you with a detailed outline for the report. You are expected to follow this outline. It was designed to show you how to present the material in an orderly manner. It also ensures that you provide all the required deliverables. You are required to submit the report two weeks after completing the experiments.

You will not be able to execute the steps in order so you need to familiarize yourself with each part before you are in the lab. This lab requires you to execute the measurements quickly or you will not be able to finish on time (and we will not extend the lab past the end of the period).

**Part 1: Static and dynamic characteristics of a first order, thermal measurement system**

In Parts I and II of the lab, you will calibrate a thermocouple against a thermistor for approximately 10 points between 0°C and 100°C. The thermistor we will use as our reference is accurate to ±0.2°C (meaning the measured value and the true value are within ±0.2°C). You will determine the thermistor constants using resistance measurements of an ice bath and boiling water bath as the temperature standards for 0°C and 100°C. While you can do this using a linear regression method, you should solve explicitly for the two unknowns using the two equations, one for each temperature.

The remaining temperatures for the thermocouple calculation will be selected using a Thermo-Scientific NESLAB RTE series refrigerated circulation bath within the range 20°C to 90°C. These baths control the temperature to ±0.1°C using resistance temperature devices (RTD). While the temperature bath temperature settings are probably accurate, you will calibrate the thermocouple against the thermistor. The TAs will show you how to establish the set-point temperature. We will have four baths preset over this range for you to save time waiting for bath to stabilize at new temperatures. You will be expected to change the bath temperature by 10°C to fill in the gaps.

**Thermocouple**

The output of a thermocouple is often provided in tabular form for different thermocouple types. We will use a type J thermocouple. The output of the thermocouple is amplified by a Monolithic Thermocouple Amplifier with cold junction compensation. The datasheet for the AD594 (attached as a separate file in the assignment) shows the output in volts for a given thermocouple input with a cold junction reference built in. The amplification of the thermocouple voltage is 193.4. Fig. 1 shows a picture of the amplifier. Connect the white wire of the thermocouple to the red post and the red wire to the black post of the input for J type. Select “J-type (594) with the toggle switch. Connect the +20 terminal from Channel 1 of the NI power supply to the red post on the “DC Power In” banana plug and –the -20V terminal from Channel 2 of the NI power supply to the black post. Do not power the amplifier yet. If you are unsure how to do this, ask a TA. Connect a BNC cable from the output to the input of the oscilloscope. You will read the output voltage of this amplifier on the oscilloscope for the static calibration and using the National Instruments A-to-D converter for the dynamic response characterization. Choose an appropriate number of significant digits when recording your data.

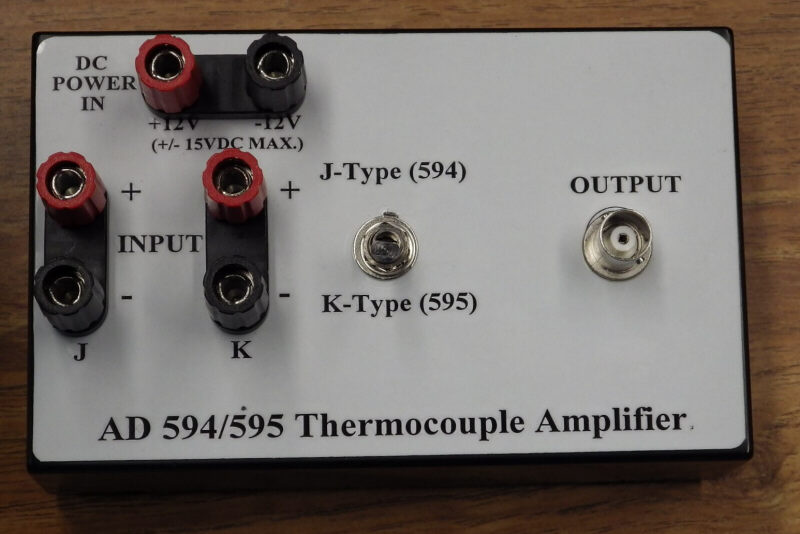


Figure 1. Image of the thermocouple amplifier.

**Thermistor**

The resistance, R, of a thermistor varies with temperature, T, following the relation



,

where Ro is the resistance (which is 10 kΩ ±0.1% for the thermistors in this lab) at the reference temperature To (typically 298.15 K), and β is an unknown parameter (ideally a constant, but not necessarily). You will use the digital multimeter (DMM) to measure R. Choose an appropriate number of significant digits when recording your data.

Once you know the thermistor constants, you can convert the resistance to temperature using the following relationship;



Organization:

There are only four temperature baths and there are 8 groups in each lab. We will have two temperature baths on two carts at the end of each bench and the two end groups can share these two baths on a single cart. They should make their measurements on the baths first while the other groups are measuring the static and dynamic response in ice water and boiling water. We are only adjusting the temperature of each bath once to minimize the time spent waiting for the bath to stabilize at the new temperature. The baths will be rotated to the other end of the bench once the first four groups are finished.

**I. Static calibration of a thermocouple measurement system using a thermistor *(Do this first if you get access to the water baths first. If not, move to the Dynamic Characterization section II, and come back to this section later.)***

Measurement tasks/steps

1. Get your boiling water bath and ice bath ready. Do not wait for them; move on to the next steps.
2. If you have not hooked up and powered your thermocouple amplifier, do so now. If you have, skip the rest of this step.
   1. See Figure 1 and read Part 1 to connect the amplifier if you haven’t done that yet.
   2. Turn on the Power Supply on the NI station by clicking on the correct icon. Set channel 1 to 12 V and channel 2 to -12 V. Make sure both channels are enabled.
3. Turn on the oscilloscope and the digital multimeter on the Desktop.
4. Connect the BNC cable from the output of the thermocouple amplifier to Channel 0 of the oscilloscope. Click on the Measure icon and select “voltage average” if it is not already selected. This will average the voltage over one scan of the scope. You can adjust the time per division to keep it from flickering too much. Make sure you record the time per division in your journal and the experimental methods section of the lab report.
5. Connect the thermistor to the input of the DMM using banana plugs. You may have to daisy chain two cables together to make it long enough to reach the baths.
6. Make a three column table in your laboratory notebook. The first column should be the bath temperature read from the LED on the water bath or the assumed fixed point bath temperatures (ice water and boiling water). The second column should be thermistor resistance in ohms and the third column should be the voltage from the amplifier.
7. For all ten water baths, insert the thermocouple and the thermistor in the water bath preferably tied together (twisties will be provided). Record the amplified voltage from the thermocouple and the resistance of the thermistor for each bath. Wait about 80 seconds for the output to stabilize. Make sure the thermocouple is fully immersed and not touching the sides of the bath.
8. Insert the bare wire thermocouple into the ice bath and record the output voltage 25 times. Since the bare wire thermocouple responds quickly, you only need to hold it in the ice water for ~3 seconds before recording the voltage. Write enough significant digits so that the values vary between measurements. For each insertion, wait for the thermocouple voltage to stabilize and record the voltage. Wait the same amount of time for each insertion. Make sure there is enough ice in the bath that you have slush and not loosely floating ice.

SAVE ALL YOUR DATA ON A FLASH DRIVE AND ON THE STUDENT DATA FOLDER FOR YOUR SECTION. ALSO, SAVE IT ON BOX, DROPBOX, ICLOUD, OR GOOGLE DRIVE.

**II. Dynamic characteristics of a first-order measurement system *(Do this first if you do not get access to the water baths first. When the baths become available, perform the steps in I. Static Calibration and finish any uncompleted steps in this section while you are waiting for the temperature baths to stabilize at the second temperature.)***

These experiments are designed to allow you to determine the dynamic response of three type-J thermocouples, one with the measurement junction exposed and two more with the measurement junction embedded in cylinders of stainless steel and aluminum, respectively. You will determine the time constant by measuring the system response to various step inputs. The response of the thermal measurement system is affected by the measurement sensor and the heat transfer conditions at the sensor surface. Each medium will have different heat transfer conditions (e.g. natural convection, forced convection, etc.) and different thermal capacities which will result in different heat transfer coefficients. Embedding the thermocouple in the cylinder changes the response of the sensor independently of the heat transfer conditions.

Measurement tasks/steps

1. Get your boiling water bath and ice bath ready. Do not wait for them; move on to the next steps.
2. If you have not hooked up your thermocouple amplifier, do so now. If you have, skip the rest of this step.
   1. See Figure 1 and Part 1 for how to connect the amplifier if you haven’t done that yet.
   2. Turn on the Power Supply on the NI station by clicking on the correct icon. Set channel 1 to 12 V and channel 2 to -12 V. Make sure that both channels are enabled.
3. Set up for voltage vs. time data acquisition using the LabView Signal Express DAQ Assistant.
   1. Select the Signal Express icon on the Desktop, choose Data Acquisition Assistant, Create New DAQ Assistant Project, Acquire Signals, DAQmx Acquire, Analog Input, Voltage, ai0.
   2. (Hook up the output of the thermocouple amplifier to the input cables from the A-D board (an NI USB-6212 DAQ). The output of the TC amplifier should be connected to the ai0 differential input (pins 15 and 16) of the DAQ. The low pin (16) must be bonded to the input ground of the DAQ, pin 28, via a jumper wire. We have wired this jumper on the DAQ, but make sure it is in place.
   3. On the Step Setup tab, set the data acquisition rate to 1 kHz and number of points to 5000. Set the sampling to N samples. This will give five seconds of data.
   4. Click the small arrow next to the Run button and choose the Run Once option.
   5. Gently grab the thermocouple bead between your fingers and see if the amplifier output changes.
   6. Click on the Data View tab and drag the icon for the channel you are recording (on the left hand side of the window) onto the graph.
   7. Set the maximum timeout to 500 seconds in the Advanced Timing tab.
4. BARE WIRE THERMOCOUPLE: Determine what would be an appropriate setting for the acquisition rate, f, and the number of samples, N, so that you can capture all of the “step” response as well as a short 1-3 second baseline and the final value. Check with a TA to verify you have selected appropriate values. Use the Run Once button to record temperature as you transition the bare wire thermocouple through the following steps. Wait ~3 seconds before making the transition so that you get a baseline. Save your data into an Excel file after each transition. Keep Excel open and it will add a new sheet for each new data file. Rename the tab each time so you know which transition the data refers to. Move quickly when moving the thermocouple between water baths.
   1. Ice water to boiling water. Select f and N yourself.
   2. Boiling water to ice water. Select f and N yourself.
   3. Ice water to air. Set f = 100 Hz, N= 12,000 (120 seconds) (*The heat transfer coefficient in air is less than that for still ice water or boiling water so the time constant will be longer. Is the final temperature the same temperature as the room temperature recorded on the weather station thermometer in the room? You will discuss this in your report.)*
5. EMBEDDED THERMOCOUPLES: Have the embedded thermocouple sit in the initial bath for at least 4 minutes. Use the Run Once button to record temperature as you transition the embedded wire thermocouples through the following steps. Wait 3-5 seconds before making the transition so that you get a baseline. Save your data into an Excel file after each transition. Keep Excel open and it will add a new sheet for each new data file. Rename the tab so you know which transition and which thermocouple the data refers to. Move quickly when moving the thermocouple between water baths. *It is unlikely you will reach the static, steady state value during these time periods – this is on purpose.*
   1. Hold each sensor in the ice water for at least 4 minutes before transitioning to boiling water. f = 100 Hz, N= 5000 (50 seconds)
   2. Hold each sensor in the boiling water for at least 4 minutes before transitioning to ice water. f = 100 Hz, N= 5000 (50 seconds)

SAVE ALL YOUR DATA ON A FLASH DRIVE AND ON THE STUDENT DATA FOLDER FOR YOUR SECTION. ALSO, SAVE IT ON BOX, DROPBOX, ICLOUD, OR GOOGLE DRIVE

**BEFORE LEAVING THE LAB:**

1. Click on “disable” in the power supply.
2. Record the temperature from the weather station in the lab.

We have organized this lab for you in two parts. The first part is to make sure you have all of your data properly analyzed. The second part is to write an internal report in response to an assignment for your manager. You must individually submit your plots and analysis first and they will be graded. You will then use the best plots and analysis for your group report.

For the first part, you must submit two and only two files – no zip files. The first document can be a Word or pdf file that contains the information that is not part of the programs and plots you are producing. The second document must be a pdf that was produced using the Publish option in Matlab. Make sure the settings in Matlab are configured so that you export pdf files – do not convert an exported HTML file to pdf.

**Deliverables for static calibration (should be determined out of lab)**

1. ***(2%)*** *(For first document)* Use the ice water and boiling water fixed point bath thermistor resistance values to determine β and R­o in the thermistor equation assuming To =298.15K. Since you have two values for T and two unknowns, β and Ro, you must solve directly for the two constants. List the two thermistor constants in a table.
2. ***(15%)*** *(For published Matlab document and code)* Plot a calibration curve for the amplified, bare wire thermocouple output voltage (y axis) versus temperature (x axis) from the thermistor resistance measurement. Use the least squares method to determine the equation for the best fit line. Your plot should show the actual data as discrete points and the best fit line only for the range of data measured. (Make sure to include units on the axes.) The equation, including units, should be listed on the plot.
3. ***(15%)*** *(For published Matlab document and code)* Use the calibration curve to convert your thermocouple voltage measurements to temperature and plot thermocouple temperature vs. thermistor temperature as discrete symbols. On the same plot, plot the best fit line, the confidence interval of fit and the confidence interval of measurement (make sure you understand the difference).
4. ***(5%)*** *(For first document)* Convert your repetitive measurements of the ice water temperature from output voltage to temperature. Compute the sample mean temperature,, and standard deviation, sx, of the 25 data repetitive points. Determine the interval in which you are 95% confident contains the population mean. Determine the interval in which you are 95% confident that ANY individual measurement will fall within. Provide all values of  ,N, , etc. and all equations that you use. You may copy and paste from the slides.
5. ***(5%)*** *(For published Matlab document and code)* Graphically compare the data from the 25 repeated points to the fit and confidence interval of fit and the confidence interval of the measurement. Restrict the minimum and maximum of the x and y axes to be slightly larger than the confidence intervals near 0°C so the comparison is easy to see. This is basically a blow up of the previous plot with the data from the 25 measurements on it for comparison.

**Deliverables for dynamic calibration of thermocouples – the goal here is to determine the time constants for each thermocouple in each situation.** Use the calibration curve to convert your voltage measurements to temperature for the dynamic section of the lab. Assume that the embedded thermocouples have the same calibration curve as the bare wire thermocouples.

Provide the requested plots for all three thermocouples for each transition. Each set of plots should be vertically registered using the Subplot command so that they all have the same time axis. They will not be “pretty” in the published Matlab document. You will have to resize and reshape them for the written report.

1. Determine the time that the thermocouples transition to the new bath.
   1. Method 1: Determine the onset of the transition from the time corresponding to the temperature changing 5 standard deviations from the baseline.
   2. Method 2: Use a sliding, first order polynomial fit to determine the time associated with the maximum absolute slope (the slope is stored in the first element of the array produced by polyfit). This will be the time and temperature when the thermocouple is actually in the new environment. Using 51 points should be sufficient for the fit centered around the point where you are determining the slope (i.e. 25 rows of data before the array index for which you are determining the slope to 25 rows after). This means that the first slope determination should start 25 rows from the beginning of the temperature vs. time data and end 25 rows from the end of the data on the last 51 point fit. Initialize the maximum slope value to zero. Keep incrementing the time step and compare the current absolute value of the slope to the maximum absolute value of the slope. If the current value is larger than the previous maximum value, replace the previous value with the current value and store the array index associated with that maximum value. After you have interrogated the whole array, define t = 0 as the time when you are at the maximum absolute slope value and define Tinitial as the temperature values at that time.
   3. You may have to smooth some of the data using the convolution tools described in slide 27 of the Matlab Tools for ME 646 PowerPoint for Lab 1a.
   4. You may assume that the last several seconds of the bare wire thermocouple data represents Tfinal for the transitions to water. Average the last 1-2 seconds of data to get this value.
   5. You must use the known final bath temperature for the embedded thermocouples to define Tfinal because the sensors will not have reached thermal equilibrium with the environment.
2. ***(25%)*** *(For published Matlab document and code)* Use the error fraction,  to determine the time constant by fitting ln(Γ) vs. t with the fit relation we derived in class for the first order fit that passes through zero. This derivation is reproduced at the end of this document. Do this for all three thermocouples for all transitions except the transition to air. Also do this for both event onset methods. (You have three thermocouples, two transitions, and two onset methods so you should have twelve sets of plots). The following plots (for each thermocouple and each transition) should be vertically registered with the same length time axis using the Subplot command.
   * 1. Provide a linear plot of lnΓ(t) vs. t that shows the data compared to the prediction based on the obtained time constant.
     2. Provide a linear T(t) vs. t plot that shows the data compared to the prediction for. The y axis should be from -10°C to 110°C and the time axis should start from the beginning of the data acquisition to the end. The y axis should intersect the time axis at the shifted t = 0. Use shifted time for the x axis – the leftmost point will be at negative time.
     3. Provide a linear plot that shows the residuals vs. time.
3. ***(20%)*** *(For published Matlab document and code)* Estimate the time constant from these data using the criterion that T(t=τ)=Tinitial +0.632(Tfinal – Tinitial). Do this for both onset methods. Provide a plot that shows the data compared to the prediction (T vs. t) and a second plot that shows the residuals vs. time. The y axis of the T vs. t plot should be from -10°C to 110°C and the time axis should start from the beginning of the data acquisition to the end. The y axis should intersect the time axis at the shifted t = 0. Use shifted time for the x axis – the leftmost point will be at negative time.
4. ***(5%)*** *(For published Matlab document and code)* Provide comparative plots that show residuals vs. time for each calculation method on the same vertical scale. Use a single plot to combine all results if they are well separated. Use multiple stacked plots if there is enough overlap that it makes it difficult to visually separate the results from each calculation method. List the value of syx on each plot.
5. ***(5%)*** *(For published Matlab document and code)* Provide plot of T vs. t for bare thermocouple to air transition. Include a horizontal dashed line indicating the room temperature.
6. ***(3%)*** *(For first document) Provide a table or tables that compare the different methods of calculating the time constant for each environmental transition and each thermocouple type. The table(s) should list the value of time constant as well as the syx for each method, thermocouple, and environmental transition. You can decide the most effective way to group the information.*

**Linear regression for one constant.**

**** 