MIDDLE EAST TECHNICAL UNIVERSITY

DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

PROCESS CONTROL LABORATORY

EXPERIMENT 1: THERMOCOUPLE CHARACTERISTICS

I. Objective

The objective of this experiment is to investigate the transient behaviour of thermocouples by observing their responses to certain inputs and to improve these responses by using passive compensators.

II. Information

Thermoelectricity and Thermocouples

Thermocouples are the thermoelectric devices which are commonly used for measuring temperature in a wide range from -270 to 2000~2300°C, depending on the material from which they are constructed.

The underlying idea of thermocouples is the thermoelectric effect, which was discovered by T. J. Seeback in 1821. The first thermocouple was constructed by A. C. Becquerel within five years of Seeback's discovery. After the discovery of the laws of thermoelectricity, thermocouples have gained great importance in temperature measurement.

It can be shown that, by using the laws of thermoelectricity, between the two ends of a metal wire which are kept constant at different temperatures T and T_{ref}, a thermoelectric voltage is produced, given by:

$$V = K(T - T_{ref})$$

Here, K is known as the Seeback constant and depends on the type of the metal. This voltage, however, cannot be measured directly, since the wires, which are to be connected to the ends of the metal to measure the voltage, will also be in the temperature field. To overcome this practical difficulty, the voltage difference between the free ends of two suitably chosen metals, whose other ends are connected and are at the temperature to be determined, is measured as shown in Figure 1.

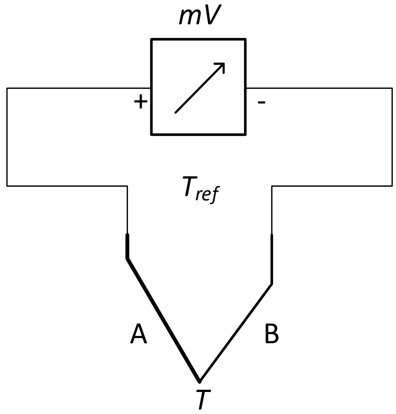

Figure 1 - Simple Thermocouple

Here the voltage difference between the free ends of the metals is given by:

$$V = K_A(T - T_{ref}) + K_B(T_{ref} - T) = (K_A - K_B)(T - T_{ref})$$

In practice, the configuration shown in Figure 2 is used to measure the temperature.

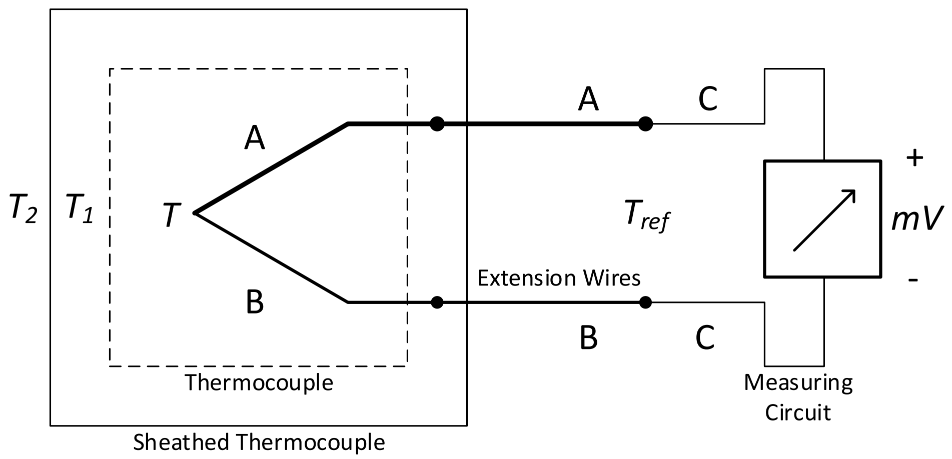

Figure 2 - Practical Thermocouple

Here the thermoelectric voltage is given by:

$$V = K(T - T_{ref})$$

$$K = K_A - K_B$$

It is seen from the expression that the thermoelectric voltage V depends not only on T, the temperature to be measured, but also on T_{ref}, the ambient temperature. If a thermoelectric voltage depending only on the temperature to be measured is required, cold junction compensation techniques must be used. However, in this experiment, the transient behaviour of the thermocouple is investigated and therefore cold junction compensation is not necessary assuming that the ambient temperature is constant throughout the experiment. In this experiment, a NiCr-Ni type (K type) thermocouple is used. As a final remark, thermocouples are categorised as unidirectional, active transducers: transducer naming thanks to their ability to convert thermal signals into electrical ones, active naming thanks to the requirement of no external power supply to achieve this and unidirectional naming due to their inability of conversion of electrical signals into thermal ones.

III. Preliminary Work

1. Let the parameters of a thermocouple be given as

h:	heat transfer coefficient
A:	area of junction
C:	specific heat of junction
m:	mass of junction
K:	Seeback coefficient.

Find the transfer function $G_1(s) = V(s)/T_1(s)$ of the thermocouple, where V is the output voltage and T_1 is the temperature to be measured, relative to ambient temperature. You may assume $T_{ref} = 0°\text{C}$.

2. Suppose that the thermocouple is in a protective tube, which is called a sheath. Assuming that the sheath behaves as a time constant element with transfer function:

$$G'(s) = \frac{T_1(s)}{T_2(s)} = \frac{1}{1 + \tau_2 s}$$

where $T_1(s)$ is the temperature inside the sheath and $T_2(s)$ is the temperature to be measured, both relative to the ambient temperature, find the transfer function $G_2(s) = V(s)/T_2(s)$ of the sheathed thermocouple.

3. Plot the variations of the output voltage of both the bare and the sheathed thermocouples, if the temperature to be measured changes stepwise. You may assume that time constant of bare thermocouple is 1 second and sheath causes an additional time constant of 10 seconds, and that both transfer functions are of unity DC gain. On the same plot, provide the step response assuming thermocouple time constant being equal to 0. You may find the following MATLAB functions useful: tf(…), step(…).

4. Time constant of the bare thermocouple is usually much smaller than the one caused by sheathing. Therefore, one may approximate the overall transfer function as a first order one. With this reasoning in mind, suppose that the sheathed thermocouple is represented *approximately* by the transfer function:

$$G(s) = \frac{K}{1 + \tau_2 s}$$

Then, the voltage generated across wires will be of the following form.

$$V(t) = \Delta V\left(1 - e^{-\frac{t}{\tau_2}}\right) + V_0$$

Find an expression of $V(\tau_2)$ in terms of ΔV and V_0. Manipulate the expression to find τ_2 in terms of $V(\tau_2)$, ΔV and V_0. You will be using this while finding the time constant from the measurements.

5. Draw the pole-zero patterns for both the bare and the sheathed thermocouples.
6. Consider RC circuit in Figure 3. Obtain the transfer function $G_c(s) = V_o(s)/V_i(s)$.

Find the values of α and T such that the compensator is of the following form.

$$G_c(s) = \alpha \frac{1 + \tau_c s}{1 + \alpha \tau_c s}$$

Considering the range of values α may obtain, which kind of a compensator does the above circuit function as? What is its DC gain? Draw the pole-zero pattern for this compensator.

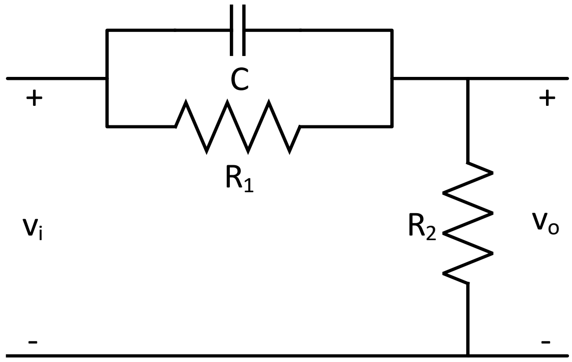

Figure 3 - Compensation Circuit

7. In order to make the measurements faster, the value of τ_c should be chosen equal to the dominant pole of the sheathed thermocouple in order to suppress its effect on the output, while the value $\alpha\tau_c$ should be chosen as the desired pole location. For example, in order to make the measurements n times as fast, the value of α should be equal to 1/n.

Suppose that $\alpha = 0.5$ and $\tau_c = \tau_2 = 10$ sec. Draw the variation of the output voltage of the compensated (sheathed) thermocouple for a unit step change in the temperature. Compare this graph with that of sheathed thermocouple you drew in step 3.

8. Obtain the transient response as in the previous step for the cases when you overestimate and underestimate τ_2 by 20%. That is, obtain the step response when $\tau_2 = 10$ sec and $\alpha = 0.5$, but τ_c is chosen as $\tau_c = 12$ sec and 8 sec, respectively, due to wrong identification. Comment on the difference(s) between these results.

IV. Experimental Procedure

1. Turn on the hot plate. During this experiment make sure that no cable is in direct contact with its heating surface.

2. Rotate the knob of the hot plate to highlight temperature setting. Click the knob, and rotate it again to adjust the temperature set point to 80°C. Click it again to confirm this setting.

3. Repeat step 2 to adjust the magnetic stirrer rotation speed to 500 rpm.

4. Click on both of the front push buttons to start the heating and stirring procedure. The screen should now be updated according to the measured values.

5. K type thermocouples, such as the one used in this experiment, have low voltage changes per unit temperature change even in their linear region ($41\mu V/°C$), which will be further diminished with the compensating circuit. In order to have measurements with higher resolution, an amplifier is employed in the experimental setup. Please assure that the gain of the amplifier is set to 100.

6. Make necessary connections between the amplifier and the thermocouple. Also make sure that two ends of the thermocouple are not in physical contact with each other.

7. Turn on the multimeter, rotating its knob to read DC voltages at the order of mV's and then connect it to the output of the amplifier circuit.

8. From the desktop, start the data logging software named Bs82-**52x**____.

9. Either from the menu bar or push buttons below it, click the Link button to connect to the multimeter. This should bring up live measurements to the window Digital Meter.

10. Wait until the temperature of the liquid bath reaches its set point 80°C ± 1°C.

11. From the menu bar of the graphical recorder window, click on Acquisition→Start to start recording the measurements.

12. Submerge the thermocouple into the liquid bath by approximately 3-4 cm by repositioning its clamp holder. This shall give a step input to the sheathed thermocouple with a magnitude of $T_{LiquidBath} - T_{Room}$.

13. Wait until thermocouple measurements reach a steady state value and stop recording by clicking on Acquisition→Stop.

14. Again from the menu bar of the graphical recorder window click on File→Export. This should bring up a pop-up window. Click on Browse, navigate to desktop, enter a filename and click Save, bringing you back to the pop up window. Choose "All Pages" setting under page scope and "Text/Data Only" under export. Click on Export button.

15. Take the thermocouple out of the liquid bath.

16. Start MATLAB, and navigate your working directory to desktop. Double click on the file you have just generated with a .csv extension. This shall bring up the import wizard. Choose "Delimited" in order to import a Comma Separated Values file, leaving the other default settings intact. Highlight the column labeled as Time. Now, you have to define the format of time so that MATLAB can interpret it correctly. Time data in the .csv file is represented in 24-hour clock (HH), followed by minutes (mm) and seconds with one digit after the decimal point (ss.S), each field separated with colons (:). In order to introduce this format, click on the pushdown menu of the column labeled as Time, select "more date formats…", scroll to the bottom, enter HH:mm:ss.S into the text field initially labeled as "Enter custom format here." and hit enter. Highlight the data you want to import (all the rows of the second and third columns except for the first row) and finally click on the Import Selection button at the top right corner. This shall create variables named Time and MainData, the latter being with the unit of mV.

17. Plot the data and examine the amplitude of the change (do not forget to save this figure as well as MATLAB Workspace). By examining this data, you are required to find the dominating time constant of measurement device.

    Hint: Consider what percentage of step response would be achieved within the period of one time constant for a first order causal and BIBO stable system. Try to locate the instant that response is reached and find the time difference between that instant and the beginning of step response.

18. Now that you have found the dominant pole of the measurement device, you are required to construct the circuit shown in Figure 3. You are given the capacitor value as $C = 47\mu F$. Using your preliminary work, and explanation provided at the last step of preliminary work, find the resistance values R_1 and R_2 to get the measurements twice as fast.

19. Connect the output of the amplifier circuit to the input of this compensating circuit. Wait until the output of the compensating circuit settles down. If amplifier circuit provides constant output (meaning that the thermocouple voltage is constant) while compensating one still continues to change, this means that charging of the capacitor takes a long time. You may **temporarily** connect small 1kΩ resistances in parallel to both R_1 and R_2 to speed up the process, and remove them afterwards.

20. Go back to the recorder software, click on File→Clear on the menu bar of Graphical Recorder. Repeat steps 12-18, but do not override your previous data and record the compensated output.

21. Take a copy of your plots/data for the report.

V. Results and Discussion

1. Determine the time constant of the thermocouple from the record obtained in the Experimental Procedure, step 18. Provide the step response plot and explain how you used this data to find the time constant τ_m.

2. Assuming, very roughly, that the room temperature is at 20°C, what is the steady state gain, K, of the thermocouple? What is the unit of K? Remember that the final temperature is equal to that of the liquid bath. Also do not forget to eliminate the effect of the amplifier circuit from your measurements.

3. Provide the step response at the compensated output. Is this response twice as fast as the one in step 1? State any possible and reasonable causes of discrepancies.

4. Is it possible to reduce the time constant of a thermocouple indefinitely using a passive compensator? Would you need another non-interacting compensator, and why? Can you obtain better results using active elements? Explain the details of application shortly but clearly.

VI. Conclusions

Write down your general conclusions and comments on this experiment.