

An Incremental Measurements and Data Acquisition Project

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Abstract

In the junior level Measurements course for Mechanical Engineering students, an incremental project forms the backbone of the course wherein several practical and theoretical topics are embodied. The goal is to familiarize Mechanical Engineering students with several electrical and electronics concepts and components used in measurement systems. The students are introduced to LabView and build their first Virtual Instrument which generates a signal in the Block Diagram and plots it on the Front Panel. Subsequent phases add a data acquisition system and a breadboard. They learn about and utilize an op-amp and build a simple “gain of 2” non-inverting amplifier to learn how an op-amp behaves solo. The op-amp is set aside and they work with thermocouple wire alone, then add a thermocouple amplifier, thereby learning about digital data acquisition systems and digital to analog conversion resolution and quantization. A limitation is discovered in the thermocouple amplifier and corrected with the use of the op-amp circuit. A pressure transducer is added, calibrated and a statistical analysis is performed. The project is consummated by combining temperature and pressure to yield a density readout. Different scaling and filtering methods in LabView are explored. A project report is written by each team.

Introduction

An incremental project forms the backbone of a Measurements course for Mechanical Engineering juniors and is summarized in Table 1.

	hardware / software used	practical experience / knowledge / concepts
Phase I	Labview – data acquisition hardware	signal generation & plotting – DAQ Assistant - scaling, frequency, amplitude – hardware software interaction
Phase II	op-amp	op-amp characteristics – impedance matching – reading a schematic – wiring a solid-state component – use of breadboard
Phase III	thermocouple wire alone	thermocouple characteristics – Seebeck Effect – Analog to Digital conversion resolution issues and sensitivity – utilizing technical datasheets
Phase IV	add thermocouple amplifier without op-amp	wiring a more complex system from a schematic – loading effect – impedance matching
Phase V	add op-amp to thermocouple amp	more complexity – practical use of op-amp – measurement system transients

Phase VI	pressure transducer	calibration – statistical analysis
Phase VII	compute density in LabView	more complexity – additional vi blocks – use of capacitors

Table 1 Project Breakdown / Summary

This project was intended to improve students' understanding of the use of software and hardware when making measurements. Specifically, this project uses LabView Software and a National Instruments Data Acquisition Board (NIDAQ). This project requires experimenters to troubleshoot and find solutions to problems that arise. Familiarity with electrical components and their representation in schematic and wiring diagrams improves as a result of this project. This knowledge will aid in future designs of mechanical systems where measurements are involved.

Phase I

Part A

Students were first introduced to LabView as a software application without a data acquisition component. Figure 1 shows the associated Virtual Instrument.

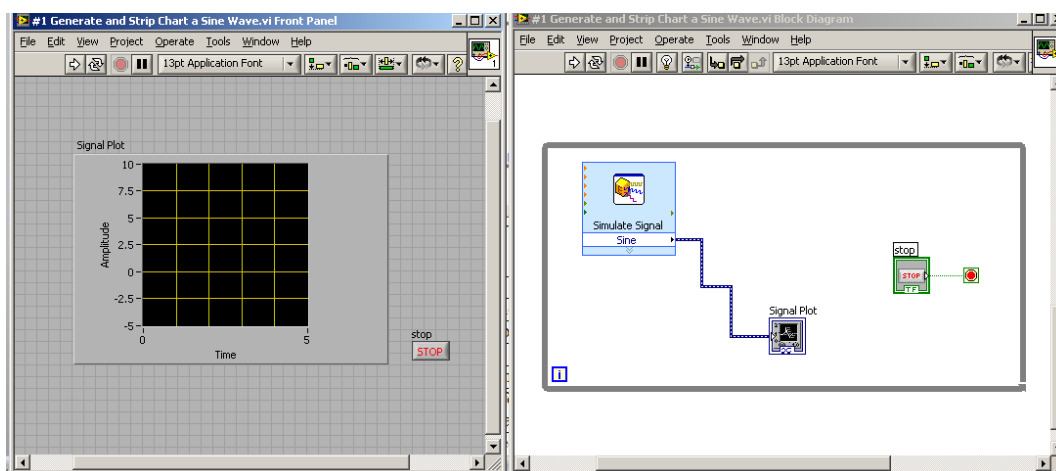


Figure 1 Phase I Part A Virtual Instrument Front Panel and Block Diagram

Part B – Output an AO

In Phase I Part B, students built upon the Virtual Instrument in Part A by adding a National Instruments data acquisition module called “the NIDAQ board” (see Figure 2). The updated block diagram with the DAQ Assistant is in Figure 3. A multi-meter was used to insure that the NI-DAQ board was actually producing a signal.



Figure 2 National Instruments USB-6008

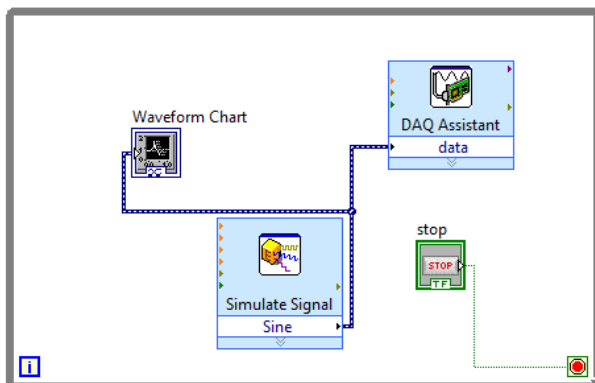


Figure 3: Block Diagram for "Output an AO to the NIDAQ board.vi"

Part C – Wrap an AO into an AI

In Phase I Part C students built upon the previous Virtual Instrument, “Output an AO to the NIDAQ board,” by adding a second DAQ Assistant block to receive an Analog Input (hereafter called an AI). The Block Diagram appears in Figure 4. The Front Panel appears in Figure 5.

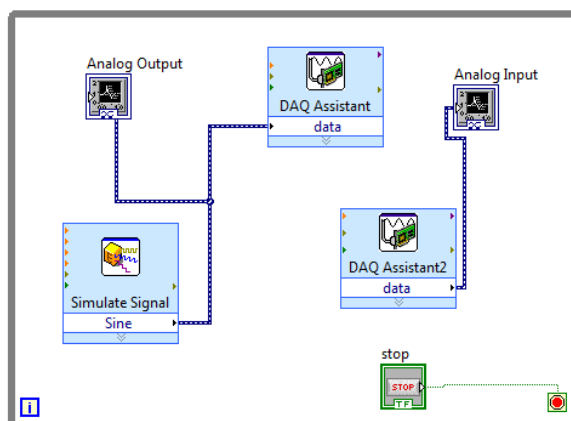


Figure 4: Block Diagram for "Wrap an AO into an AI from_to the NIDAQ board.vi"

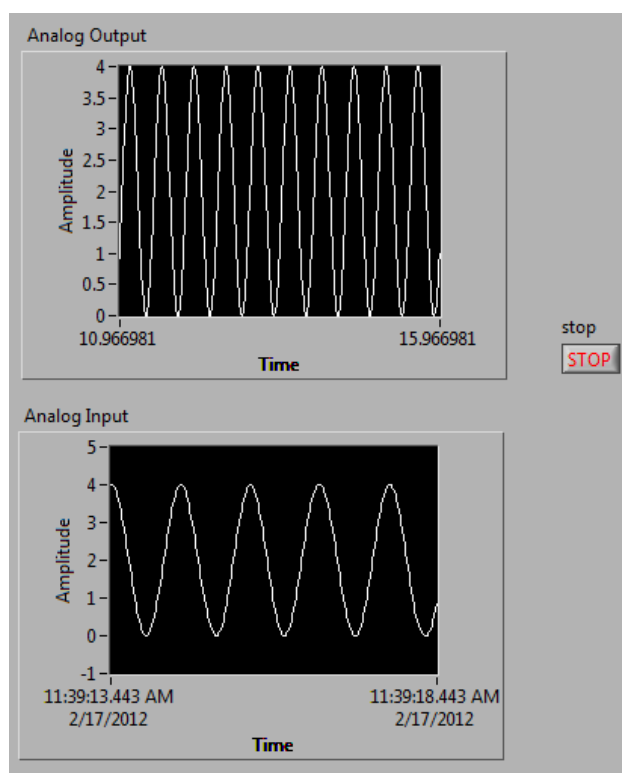


Figure 5: Front Panel for run of "Wrap an AO into an AI from_to the NIDAQ board.vi"

Phase II

In Phase II, the operational amplifier (op-amp) was added. The goal - to highlight the op-amp characteristics and its uses and to gain further experience and understanding of the use of the data acquisition system. The NIDAQ board, at the behest of the same LabView “VI” used in Phase I Part C, output a sinusoidal voltage signal (AO) and received an amplified input voltage signal (AI). The op-amp circuit was set up as a non-inverting amplifier as shown in Figure 6. The amplification, K , is defined as shown in Eq 1. The resistor values were chosen to yield a K of 2. Therefore, whatever voltage was output (AO) by the NIDAQ was to be received again (AI) amplified by 2. The wiring diagram is shown in Figure 7. The output voltage sinusoid was set to an amplitude of 2 V peak-to-peak, with an offset of 1 V. The plots in Figure 8 show the AO and the AI which has been amplified by 2.

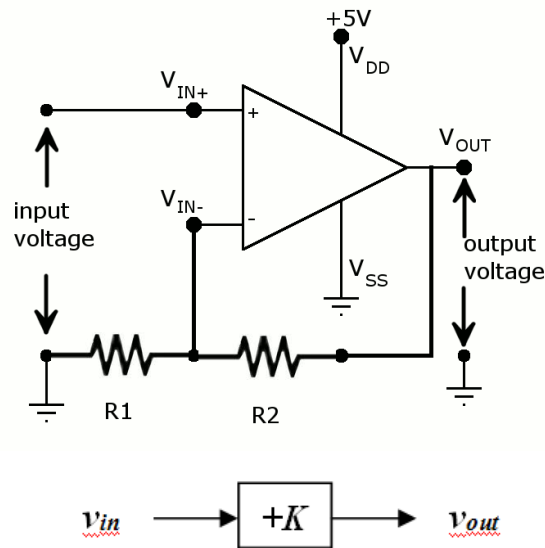


Figure 6 Non-inverting amplifier schematic and block diagram

$$v_{out} = K * v_{in} \quad \text{where } K = 1 + \frac{R_2}{R_1} = 1 + \frac{10 \times 10^3 \Omega}{10 \times 10^3 \Omega} = 1 + 1 = 2 \quad \text{Eq. 1}$$

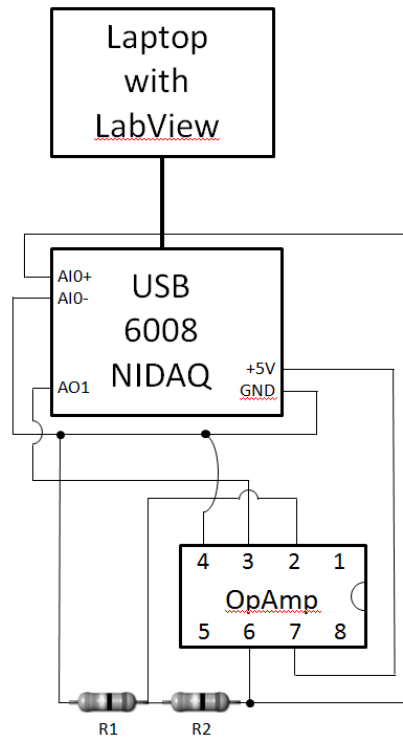


Figure 7 Phase II Wiring Diagram with the op-amp

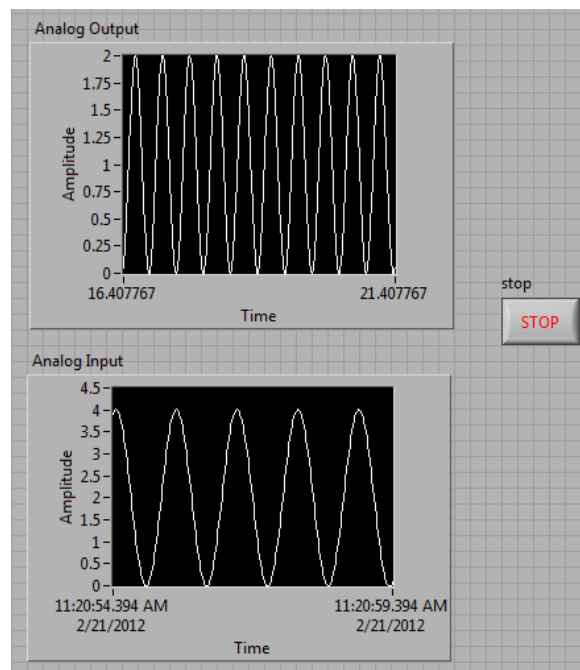


Figure 8 Phase II Front Panel showing AO and AI Voltages Using the op-amp

Phase III

The goal of Phase III was for students to work with the thermocouple wire and learn about analog to digital conversion resolution. The thermocouple wire alone was used as an analog input (AI) into the NIDAQ board. The preceding LabView file “Wrap an AO into an AI from_ to the NIDAQ board” was opened and the “Analog Output” waveform chart and DAQ Assistant were deleted.

Before the experiment was run, expected voltages and resolution were determined. Based on Table I in the AD594/AD595 Specifications Datasheet¹, "Output Voltage vs. Thermocouple Temperature," the expected voltage for J type thermocouple wire associated with 0°C (ice water) and 100°C (boiling water) were found, namely, 0°C corresponds to a voltage of 0 mV and 100°C corresponds to 5.268 mV. Therefore, when the thermocouple alone is placed in these two phases of water, those are the two voltages that should be read from the waveform chart on LabView.

However, the Analog Input (AI) resolution for the NIDAQ board had to be examined to see if it could show voltages this precisely. First, the minimum range of the NIDAQ USB 6008 had to be found. From the NIDAQ Datasheet², this was found to be ± 1 V. The resolution of the USB 6008 is 12 bits or $2^{12} = 4096$ quantization steps. With these two values, the corresponding best resolution in Volts per step was calculated in Eq 2.

$$resolution = \frac{volts}{steps} = \frac{2 V}{4096 steps} = 0.488 \frac{mV}{step} \quad \text{Eq. 2}$$

Using the two extreme temperatures and corresponding expected voltages, the best resolution in degC per step is shown in Eq 3.

$$resolution = \frac{2000 mV}{4096 steps} \cdot \frac{100^{\circ}C - 0^{\circ}C}{5.268 mV - 0 mV} = 9.269 \frac{degC}{step} \quad \text{Eq. 3}$$

Students recognize that this resolution is quite poor and this realization leads to the use of a thermocouple amplifier in the next phase.

Phase IV

In this phase, the thermocouple amplifier was added to the circuit. The system consisted of the NIDAQ board, the thermocouple, and the thermocouple amplifier. From Table I in reference 1, the expected voltage associated with 0°C (ice water) and 100°C (boiling water) was found. Based on this table, for a type J thermocouple, a temperature of 0°C corresponds to a voltage of 3.1 mV and 100°C corresponds to 1022 mV.

The schematic diagram for the thermocouple amplifier was found in reference 1 and is reproduced in Figure 9. The LabView vi for this phase consists of just one analog input as shown in Figure 10. Students checked the thermocouple performance with ice water and boiling water as shown in Figure 11. The voltages measured and output in LabView are shown in Figure 12.

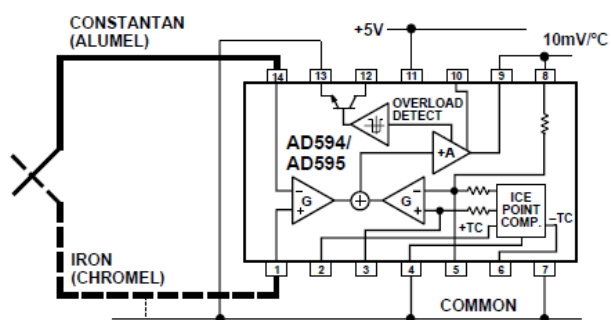


Figure 9 Schematic of the Thermocouple Amplifier

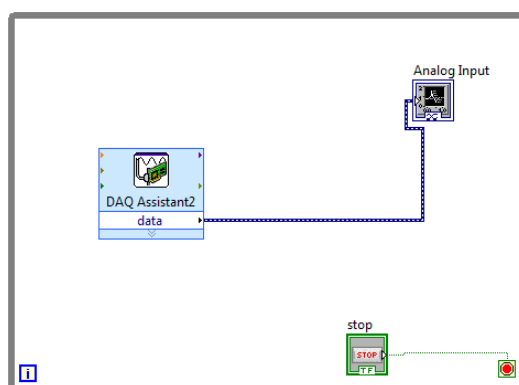


Figure 10 Phase IV Block Diagram for the Thermocouple Amplifier

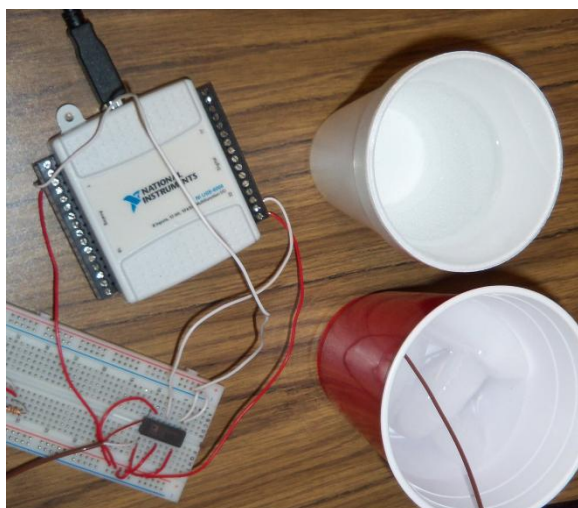


Figure 11 Checking Thermocouple Amplifier performance

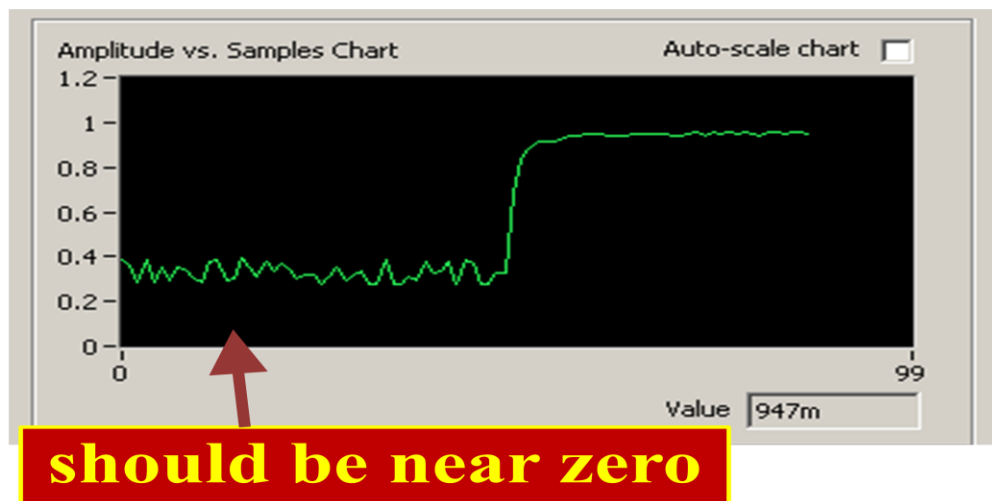


Figure 12 Phase IV Ice to Boiling Water voltage readings

As seen in Figure 12, the voltage measured in boiling water was close to the expected 1 Volt. But in ice water the expected reading of near zero was not realized. This puzzled the students and was explained to them in the lecture portion as being caused by a mis-match of component impedances.

Students are reminded that when dealing with 2-component systems, ideally, the system should have an output (source) with low impedance and an input (load) with high impedance. In the present circuit, the output was from the AD594 thermocouple amplifier, and the input went to the USB-6008 NIDAQ. In Figure 13 and Eq. 4, E_S is the voltage and R_S is the resistance (impedance). The subscript "L" refers to the load and "S" to the source. From the data sheets and specifications of the two pieces of hardware, R_L was found to be 145 k Ω and R_S to be 50 k Ω . This yields a ratio of the voltages, E_L/E_S , of 0.743. Ideally, this ratio should approach 1, as that would mean almost no voltage drop. It was concluded that the impedance matching of the two components was far from ideal. In the next phase, the op-amp comes to the rescue.

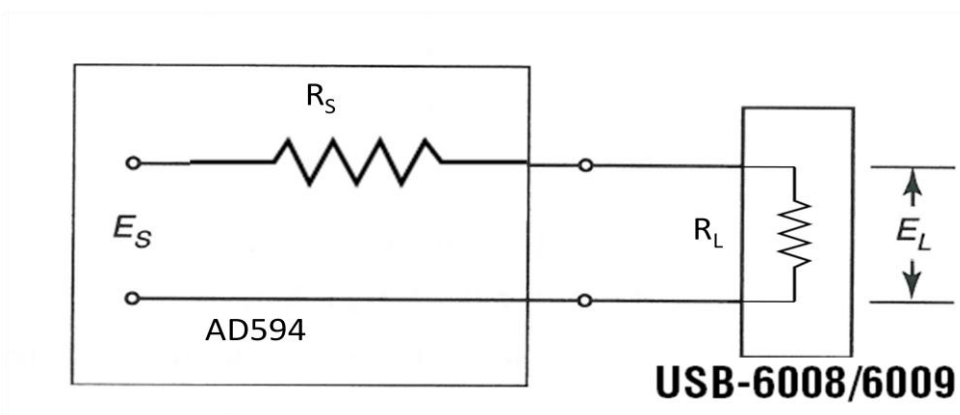


Figure 13 Source and Load designations in Thermocouple Amp Setup Phase IV

Phase Va

In this phase the op-amp is added to alleviate the impedance mis-match. To make it more relevant to Mechanical Engineering students, the op-amp can be thought of as analogous to a power control actuator. It transmits the signal from the thermocouple to the NIDAQ board without allowing it to be loaded down. The particular op-amp circuit used doubled the voltage. Therefore, a voltage divider consisting of two equal resistors had to be added between the thermocouple amplifier and the op-amp. Consequently, the input voltage from the thermocouple was not distorted by the op-amp in that regard. Figure 14 shows the wiring diagram of the total system.

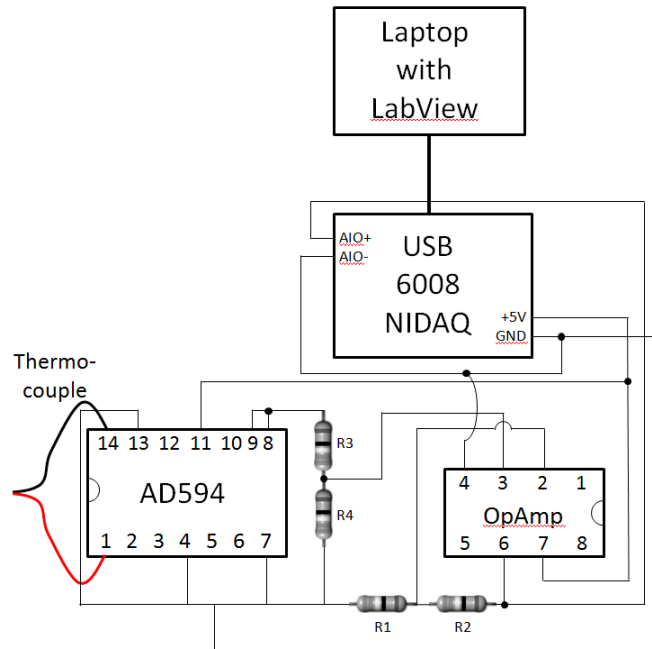


Figure 14 Phase Va Wiring Diagram

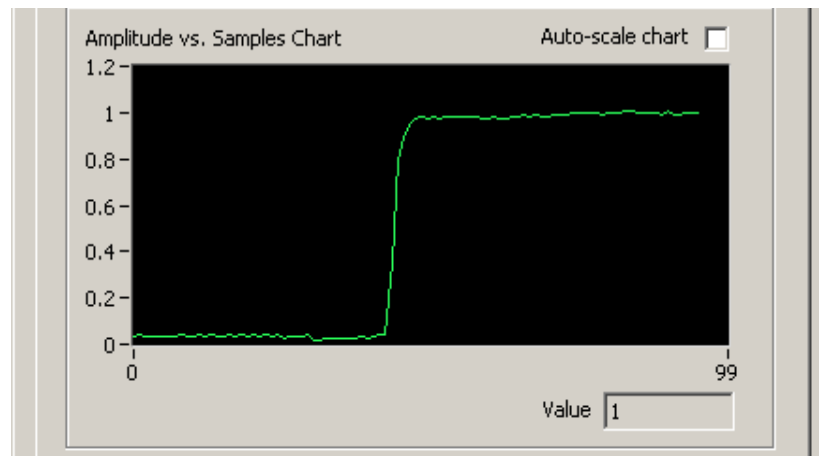


Figure 15 Phase Va Ice to Boiling Water voltage readings

The same LabView program as in Phase IV was run and thermocouple performance was again checked as before with ice water, and boiling water. The voltages measured and output in

LabView are shown in Figure 15. As hoped, the voltage reading in the ice water was nearly zero and in the hot water was nearly one – much closer to the expected results indicating that the op-amp was successful in facilitating component impedance matching.

Phase Vb

In this phase students determine the time constant of the thermocouple system. A “Write to Measurement File” block was added to the .vi file used from the last phase. This block created a notepad file with the time and thermocouple voltage for each run (seen in Figure 16).

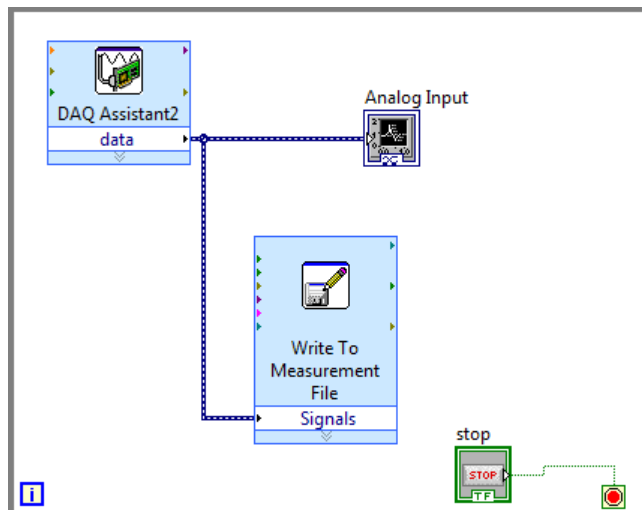


Figure 16 Block Diagram for Phase Vb

The thermocouple was first placed in the ice water and the vi started recording. Once the analog input waveform chart stabilized at the ice temperature, the thermocouple was quickly moved into the boiling water. After the analog input waveform chart stabilized at the hot temperature, the run was stopped.

The file with the time and thermocouple signals for the run was then copied into a Microsoft Excel Spreadsheet. The average thermocouple signal value was found for both the ice water portion and the boiling water portion of the run. The time constant, or the time it took to reach 63.2% of the boiling temperature from the ice temperature, was calculated to be 0.069781 seconds. Such a small time constant shows that the thermocouple system has a very fast reaction time to step changes in input.

Phase VIa

In this phase, a pressure transducer was added to the system. The wiring diagram in Figure 17 shows how the pressure transducer was integrated into the entire system, but the thermocouple amp and op-amp were temporarily disconnected until Phase VII.

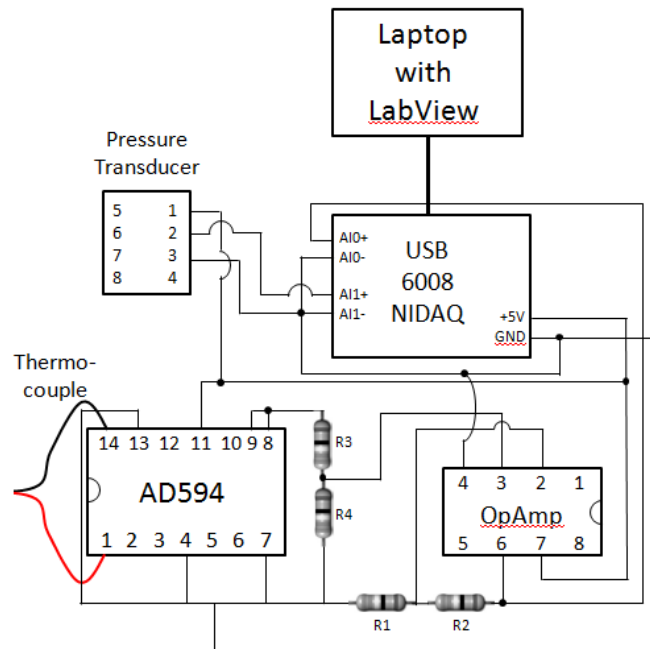


Figure 17 Wiring Diagram for Phase VI and VII

Students updated the vi incrementally and checked the operation after each change. First the DAQ Assistant was edited to bring in two AIs (temperature and pressure) and a splitter was added to separate the signals for plotting. Scaling was then done in the DAQ assistant (see Figure 18) so that the plotted and recorded values are in engineering units (temperature and pressure) instead of voltage as shown in Figure 22. The students were asked to switch the scaling from the DAQ Assistant to a separate Scaling Block as seen in Figure 19 and Figure 20. Finally, the students added a Filter Block to smooth out the temperature reading as seen in Figure 20 and Figure 21.

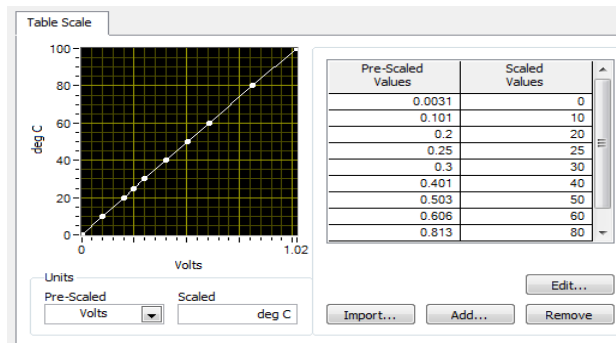


Figure 18 Temperature Scaling in the DAQ Assistant

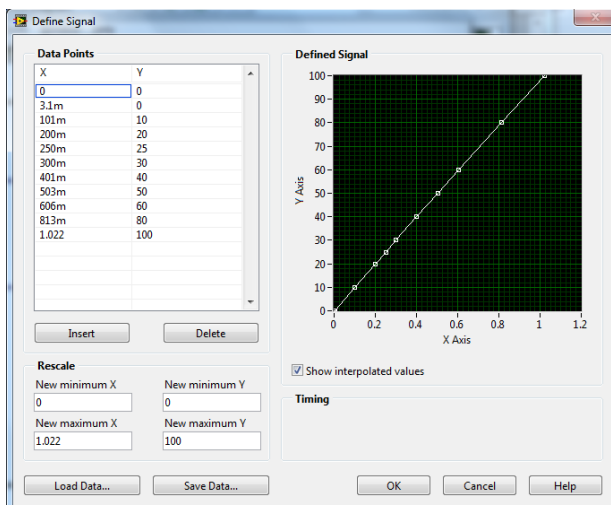


Figure 19 Temperature Scaling in the Scaling Block

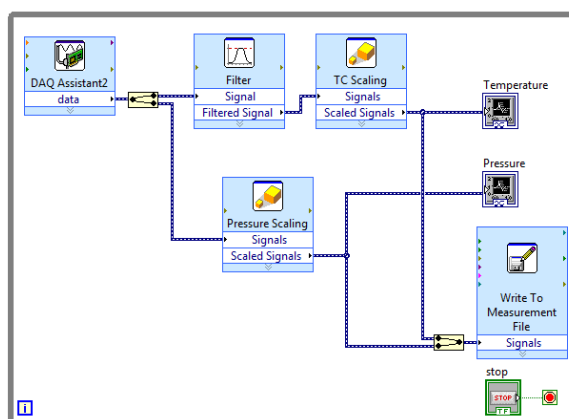


Figure 20 Final Block Diagram for Phase VI

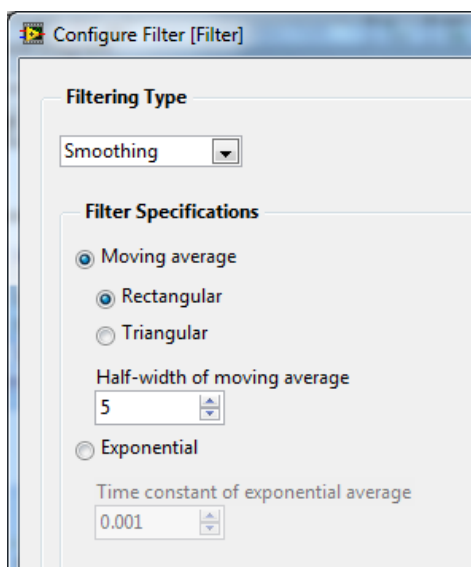


Figure 21 Filter Dialog Box

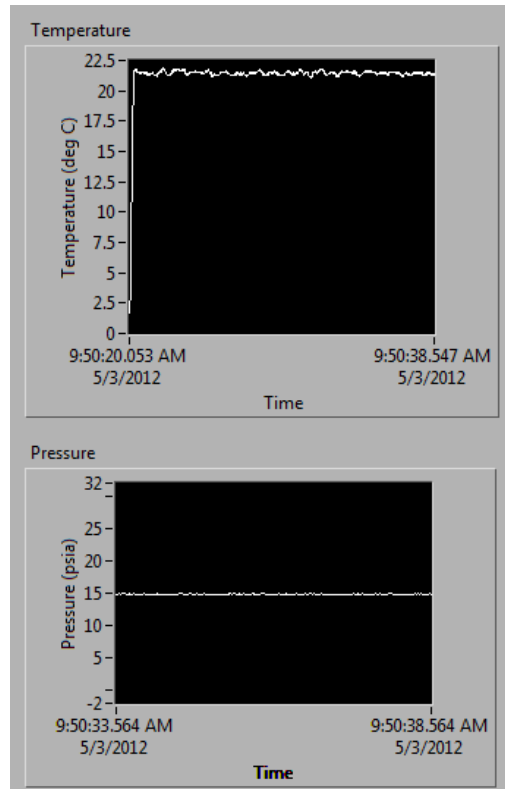


Figure 22 Front Panel for Phase VI – Engineering Units

Phase VIb

The goal of this section was to calibrate the pressure transducer. A calibrated standard gauge was connected to a master pressure pump. Each group attached a plastic tube from the master pressure pump to their pressure transducer so that all pressure transducers experienced the same pressure. Readings were taken by each group and shared. Each group loaded the data into EXCEL and determined the slope and intercept for a linear calibration best fit as shown in Figure 23. A statistical analysis was done on the resulting data.

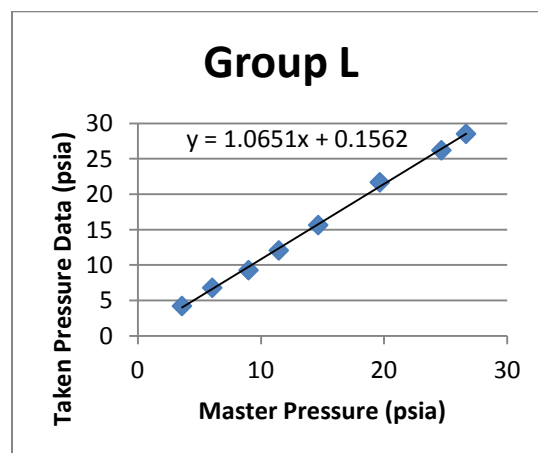


Figure 23: Example Pressure Calibration Plot

Phase VII

The goal of this final phase was to use the pressure and temperature measurements to compute air density. When the pressure transducer, op-amp, and the thermocouple amplifier were all running, they all used power from the same NIDAQ board supply. The digital switching on board the pressure transducer caused some fluctuations in the power supply voltage which appeared as noise on the temperature readings. So a capacitor or two had to be added to the system, straddling the 5 V power supply and ground. Since capacitors store electrical energy, they were used to smooth out the supply voltage in a similar manner as springs store potential energy for a later use in a mechanical system or as accumulators in a hydraulic system.

The density calculation was computed in LabView by adding a Formula Block and output to the Front Panel as a numeric display.

Bibliography

1. Analog Devices “AD594 / AD595 Monolithic Thermocouple Amplifiers” Norwood, MA, 1999. Available
WWW: http://www.analog.com/static/imported-files/data_sheets/AD594_595.pdf
2. National Instruments “Low-Cost, Bus-Powered Multifunction DAQ” USA, 2012.
Available WWW: http://sine.ni.com/ds/app/doc/p/id/ds-218/lang/en#fntarg_2

Biographical Information

Lawrence has been full time faculty at SLU since January 1995. Undergraduate courses he is involved with include Freshman Engineering, Introduction to Computer Aided Design, Introduction to Aeronautics and Astronautics, Aircraft Performance, Stability and Control, Flight Simulation, Aerospace Lab, Mechanical Measurements and Senior Design.

His 14+ years of full-time industry experience plus over 15 years part-time consulting include flight simulation, aviation accident flight-path reconstruction, analysis and animation, stress analysis and flight testing.

Larry holds both a Bachelor of Science degree (1978 - magna cum laude) and a Masters degree (1994 - with distinction) in Aerospace Engineering. He is a member of ASEE and a senior member of the American Institute of Aeronautics and Astronautics.