Langmuir Probe System Design

The Langmuir probe voltage control and current measurement system is controlled by a National Instruments Data Acquisition (DAQ) module which is connected to a computer via a USB connection and controlled by a LabVIEW program. The hardware portion of the system consists of the DAQ, voltage amplification circuitry, and current measurement/protection circuitry. The voltage amplification and the current measurement circuitry are supplied by a repurposed project built by Philip Desautels that was used for analog control of a Langmuir probe. The original project used potentiometers to control the generation of a voltage waveform of varying amplitude (+/- 10 V max) and frequency. This signal was then sent to an output port for monitoring of the generated signal and was also sent to the voltage amplification circuit to increase the voltage by a factor of 10 to give rails of +/- 100 V. In order to use this box and circuitry, the waveform generation was disconnected from the output and from the input to the voltage amplification circuit. This turns the output connection into an input connection as it is directly wired to the amplification circuit and nothing else after the modification. Once the waveform is amplified, it is sent to an output BNC connection that can be connected to the Langmuir probe to supply the desired voltage. The voltage is connected to the probe through an operational amplifier configuration to allow current collected by the probe to flow back into the system and through a desired resistor to create a measureable voltage proportional to the current without allowing any of the current to go back into the rest of the circuitry and cause potential damage. Therefore, this op amp serves as a current protection to the rest of the circuit as it will source or sink current to or from the probe as needed. The voltage across the measurement resistor is measured by the DAQ and converted to the proper current value using Ohms Law. The voltage output from the DAQ (analog output 0) is also measured by the DAQ (analog input 0) to create a data file consisting of voltages and current voltages that represent the outputs of the system. The system is set up so that 1 V = 1 mA for the current voltage readings. This has been independently verified through testing and calibration. The voltage amplification circuit is needed because the DAQ can only output +/- 15 V and a larger voltage range is required for implementing a Langmuir probe. Ideally the amplification would be a constant value across the entire voltage range. This system was set up with the intent of achieving a constant amplification of 10 times the input. However, it was discovered that the amplification is not exactly 10 or exactly constant and thus needed to be calibrated.

CALIBRATION

The first test conducted was to determine the stability and error in the output voltage of the DAQ. To conduct this test, the DAQ was programmed to output a constant voltage and this was measured by a voltmeter. The measurement points we randomly selected between +/- 10 V. The results of this test are shown in figures 1 and 2. Figure 1 shows a plot of measured output voltage versus set voltage. This plot appears to be quite linear. However, upon further investigation of the data set, it is not perfectly linear. This is exemplified in figure 2 where the difference between the output voltage and the desired or set voltage is plotted versus the set voltage. Here it can be seen that the difference changes and grows in magnitude as the voltage moves away from 0 volts which shows that we do not achieve perfect linearity. The maximum error that was measured was +/- 0.03 V. It is also worth noting that the output at all voltages is stable to one hundredth of a volt.



**Figure 1**



**Figure 2**

The main purpose of this test was to show that the programmed voltage into the DAQ is the same as the voltage coming out of the DAQ. This was achieved and shows that the output voltage is stable and accurate to within a maximum error of 0.03 V.

Although the first test is good to have, the most important calibration in terms of voltages is what are the output voltages from the voltage amplification circuit that correspond to the programmed DAQ voltages. To conduct this calibration, the same process was used as in the first test but this time the measured voltage was measured after the amplification circuit. The first results of this test are shown in figure 3, with the blue curve representing all acquired data points. From this figure it can be seen that at a certain voltage on the positive and negative extremes, the amplification circuit output becomes constant. This is most likely do to some component hitting a voltage supply rail that it cannot surpass. The maximum values are -73.98 and 76.85 volts and are achieved with set voltages of -6.75 and 7.07 volts respectively. Any of the data points outside of these maximum values are not of use to the calibration curve fitting as these maximum values will never be exceeded. Therefore, also on figure 3 is a plot of the useable data set, i.e. all points in between the two maximum values in green. The first major result of the calibration is the existence and identification of these maximum output voltage values and their corresponding inputs.



**Figure 3**

The second major result of the calibration is that from figure 3, the data set appears to be approximately linear within the useable data range. To test this, a linear function was fit to the data set using a Least Squares fitting technique. The best fit line to the data set yielded a slope, or amplification, of 10.94 which right away shows discrepancy from the original design which was intended to be a 10 times amplification. In order to test the accuracy of this linear fit, a residual analysis was completed. The residual was calculated by using the linear function to calculate the predicted output voltage based on the programmed voltage and subtracting this result from the real measured amplified output voltage. The result of this analysis is shown in figure 4 with residual plotted against programmed voltage with the blue curve representing the results for the linear fit. As can be seen, the residuals are quite large with obvious room for improvement. Investigation of improvement led to testing different polynomial functions for the fitting function and calculating the corresponding residuals. The results of two other fitting cases are also plotted in figure 4 with a cubic residual shown in green and a fifth order polynomial residual shown in red. It is quite obvious to see that the most accurate fit (the fit that minimizes the residual) is the red curve or the fifth order polynomial. With this fit, the highest residual or error in predicted voltage is +/- 0.02 V. Even though it seems odd for an amplification system that is intended to be a 10 times multiplication system to have a fifth order polynomial fit to the amplification, this function minimizes the error in the prediction model which is the most important fact. The existence of the fifth order fit is most likely due to errors in the system that makes the amplification non-linear and result in a system that needs to be approximated by a higher order polynomial.



**Figure 4**

The purpose of having this calibration is two-fold. First, we obviously need to know what the output voltage is for any given input voltage to be able to use the Langmuir probe system accurately to measure plasma properties. Second, the function is used in the LabVIEW program in an inverse fashion to calculate the required programmed voltage needed to generate the desired amplified output. The reason for this is to provide a user friendly system where the user does not need to know the amplification details, only the final output stage. With this inverse conversion, the user can input the desired voltage or voltage range into the LabVIEW program and it will calculate the required voltage(s) to output from the DAQ to generate the requested final output voltage(s). In order to develop and rationalize the use of such an inverse function, a fifth order polynomial was again fit to the data set to give an equation to calculate DAQ voltages based on desired (or in terms of the data set, measured) voltages. As with the previous fit, a residual analysis was conducted to show the difference between the calculated amplified voltages and the actual amplified voltages versus the measured voltage. The result of this is shown in figure 5. As can be seen, the largest residual is very small (2x10-3 V) which is a very good result.



**Figure 5**

The final test for the accuracy of the calibration techniques and fitting functions that have been chosen is to take a new, independent data set using the LabVIEW program and voltage amplification in full capacity. For this test, a desired output voltage was entered into the LabVIEW program to be converted to a DAQ set voltage and the resulting amplified voltage was measured. If the difference between the set amplified voltage and the measured amplified voltage is small and within reasonable tolerance, then the calibrations can be considered accurate and complete. The results of this test are shown in figure 6 where the y-axis is the result of the measured voltage minus the set voltage. The error bars on the plot represent the fluctuation observed in the measurement of the set voltage. As the voltage moved farther and farther away from zero, the fluctuation in measured voltage increased and thus the error in measurement became larger. The first conclusion that can be drawn from this figure is that not only are the errors smaller closer to 0 V but the difference is smaller closer to 0 and thus the accuracy is highest around these values. This makes sense as the reproducibility of a measurement is much higher in a regime where the outputs are more stable. In a voltage range of approximately -40 to 40 V the difference is small enough that the fitting function chosen appears to be a very good choice. Outside this range, the difference starts to become larger and in some cases cannot be considered to be 0 even within error. This fact has potential for a cause for concern; however the worst difference measure was only 0.06 V which is not a ridiculous error especially when it only occurs at the higher end of the voltage range which may not be used as extensively as the middle of the range.



**Figure 6**

Another way to look at these differences is to calculate the percent difference and plot this versus the set voltage as was done in figure 7. Here it can be seen that the worst case scenario of a measured difference is 0.09% and the worst case scenario (included from error bars) is a difference of 0.3%. This result is extremely satisfying as a calibration result. Anything less than 1% across the board for this type of calibration would have been acceptable, but to be down below 0.3% is very comforting and confirms a good calibration and choice of techniques and fitting functions.



**Figure 7**