Introduction to Sensors, Instrumentation, & Measurement

Final Project Report

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I. Theoretical Analysis and Circuit Aspects

Our chosen sensor is a string gauge, a mechanism that changes resistance based on the strain applied on two micro-thin wires within the gauge. Its transfer equation can be defined as the following:

$$\frac{\Delta R}{R} = G_F \frac{\Delta L}{L}$$

$$\frac{\Delta R}{120\Omega} = 2.1 \frac{\Delta L}{L}$$

$$\Delta R = 252 \frac{\Delta L}{L}$$

where G_F is the gauge factor (it is 2.1 for our sensors), R is the starting resistance of the strain gauge (120 Ω in our case), ΔR is the change in resistance, ΔL is the local change in the length of the material, and L is the initial unstretched length. The ratio of lengths is known as the mechanical strain. Since strain is usually quite small, the change in resistance is also quite small. Strain is a normalized measure of how much the material deforms.

We will be computing the colloquially named "grip" which is applied to our mechanical device through the strain felt by the gauge when the device undergoes pressure. To actually connect our voltage change to the strain applied, we will use the circuit, shown in figure 2, where the only dynamically variable component is the string gauge. In other terms, when the pressure is applied to our mechanism and the string gauge undergoes strain, the resistor value within our circuit will change, consequently affecting the output voltage value we measure. Our transfer equation can be boiled down to the following equation:

Equation 1: $V_{out} = V_{ref} + G(V_+ - V_-)$

In the above expression V_{out} is the voltage on pin 6, V_+ is the voltage on pin 3, V_- is the voltage on pin 2, and V_{ref} is the voltage on pin 5. Note that V_{ref} is set to 2.5V in our experiment. When we measure V_{out} relative to V_{ref} , we can measure the change in voltage caused by the beam being bent up or down. In turn, G can be computed through:

$$\text{Equation 2: } G = 1 + \frac{10\,000\,\Omega}{R_F}$$

G is the gain in this situation and is completely dependent on the value of R_F, where R_F is the value of the reference resistor between pins 1 and 8 shown in figure 1. Our gain is equal to 501 due to the fact that our chosen reference resistance is 200 Ohms, as shown in figure 2.

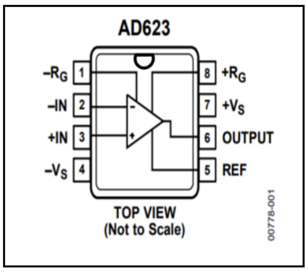

Figure 1: The pins allocation and circuit diagram for the AD623 chip used.

We should then first compute what our V_+ and V_- should be:

$$V_+ = V_{in} - I_{SG}R_{Total-SG} \,|\, V_- = V_{in} - IR_{Total}$$

Where $R_{Total - SG}$ and I_{SG} are the current and total resistance of the wheatstone bridge leg that includes the string gauge. Additionally R_{Total} and I are the current and total resistance of the other wheatstone bridge leg. We can then individually compute these values

$$R_{Total-SG} = (120 + \Delta R + 115 + 10)\Omega \,|\, R_{Total} = 242\,\Omega$$

$$I_{SG} = \frac{5\,V}{R_{Total-SG}} \,|\, I = \frac{5\,V}{R_{Total}}$$

We can then compute both legs of equation 4:

$$V_+ = 5(1 + \frac{120}{225+\Delta R})\,V \,|\, V_- = 2.5\,V$$

Finally, by inserting both of these values into equation 2, we can determine a transfer equation between the output voltage from the circuit and the strain the string gauge undergoes:

$$V_{out} = 2.5\,V + 501(5(1 + \frac{120}{225 + \Delta R})\,V - 2.5\,V)$$

$$V_{out} = 1251\,V - \frac{300\,600\,V}{225 + 252\,\frac{\Delta L}{L}}$$

We will later relate the strain and input force through a transfer equation tailored to the geometry and specific situation of our mechanism.

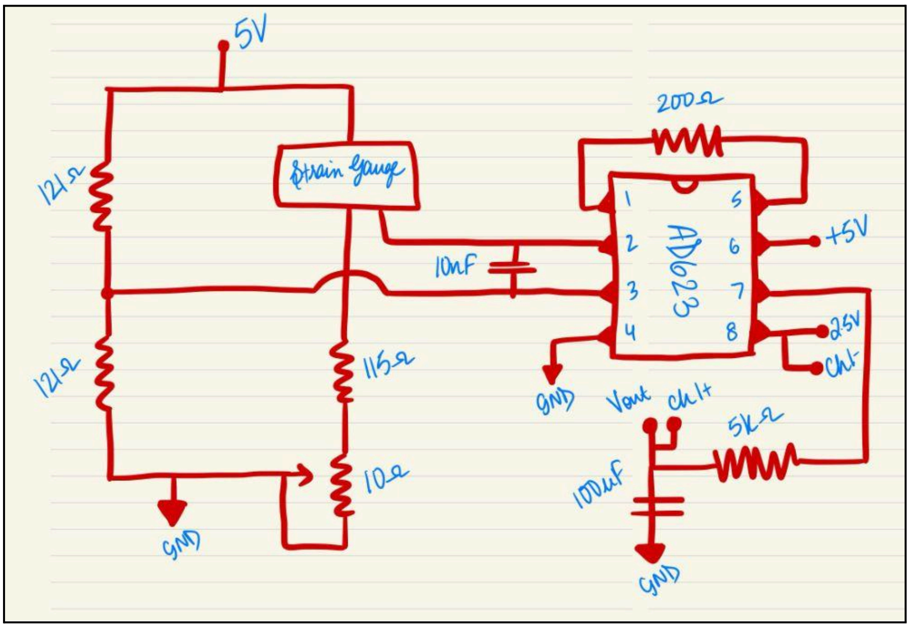

Figure 2: *Circuit diagram for our amplified and filtered string gauge-based "grip" (force) strength tester. Includes a low-pass filter of 0.5 RC and a gain of 501.*

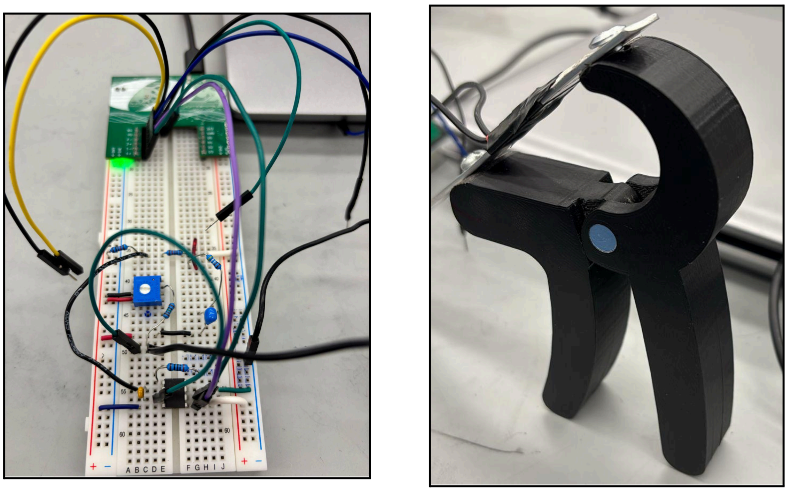

Figure 3: *Our circuit connected to the grip strength hand exerciser via the strain gauge.*

II. Circuit Description

1. *Wheatstone Bridge:*

The strain gauge is placed in one leg of a Wheatstone bridge, along with two fixed 121 Ω resistors and two additional balancing resistors (115 Ω and 10 Ω). When no strain is applied, the bridge is close to balanced and the output is close to zero. When the strain gauge is stretched or compressed, its resistance changes slightly, creating a small voltage difference across the bridge.

2. *Instrumentation Amplifier (AD263):*

The small voltage difference from the bridge is amplified using an AD623 instrumentation amplifier. The gain is set by a 200 Ω resistor between pins 1 and 8. This boosts the signal so small changes in strain create noticeable changes in output voltage. The reference pin (V_ref) is connected to 2.5V to center the output signal around 2.5V, allowing us to measure both positive and negative changes.

3. *Input Filter:*

A 10 nF capacitor is placed across the amplifier's differential inputs. This acts as a low-pass filter to reduce high-frequency noise before amplification.

4. *Output Filter:*

After the amplifier, the signal passes through a 5 kΩ resistor and a 100 µF capacitor, forming a second low-pass filter. This smooths the output voltage and helps eliminate noise, giving a clean and stable signal for data collection.

III. Bode Plot

The circuit is tuned for accurate, low-noise strain measurement. The Wheatstone bridge provides a sensitive means of detecting resistance changes, the AD623 amplifier offers high gain with a stable reference offset, and the input and output filters collectively suppress unwanted noise. The chosen component values and filter characteristics reflect a design optimized for stable, low-frequency strain monitoring. These aspects can be observed in figure 4.

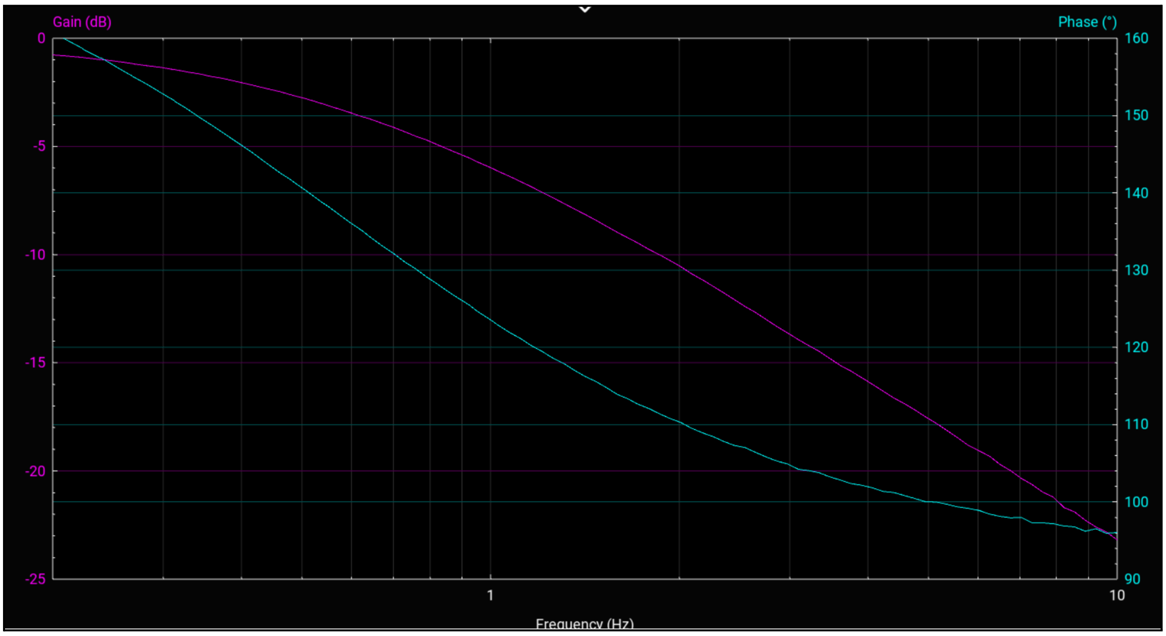

Figure 4: Bode plot of the gain and phase of our circuit with the 200-ohm gain resistor removed. A cut-off frequency of 0.318 Hertz can be observed as the inflection point for the steady decrease of the gain.

IV. Data Analysis

To convert the voltage signal into physical force measurements, a calibration procedure is performed. Known masses are applied to the sensor and corresponding output voltages are recorded. These masses are converted into force in newtons using the equation.

$$F = \left(\frac{m}{1000}\right) \cdot 9.80665$$

where m is the mass in grams. A linear regression is then performed on the resulting (voltage, force) data pairs to establish an empirical relationship of the form:

$$F = aV + b$$

However, the sensor is positioned at a 45-degree angle relative to the direction of applied force. Because strain gauges measure the normal component of strain, the measured strain is related to the actual axial strain by a factor of $cos^2(45^\circ) = 0.5$. Therefore, to compute the true axial force, the force computed from the calibration curve must be corrected by a factor of two:

$$F = 2(aV + b)$$

This final equation provides a direct conversion from the measured output voltage to the true applied grip force. It incorporates both the calibration-derived linear model and the geometric correction due to sensor orientation, ensuring the resulting force values accurately reflect the mechanical input to the system. The calibrations curves can be seen in figure 5:

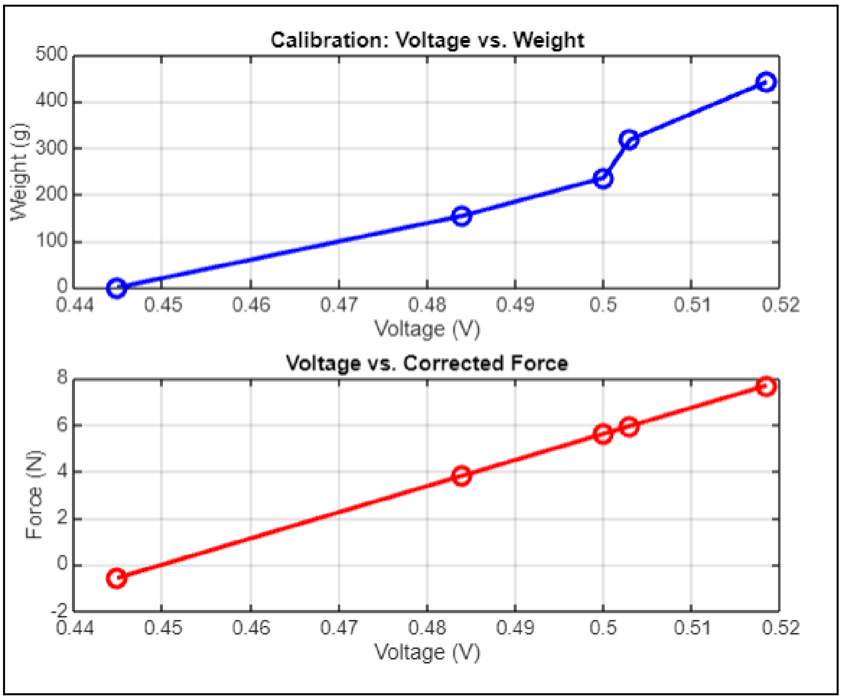

Figure 5: The subplots of calibration (Weight vs Voltage) and correlation between Voltage and final Force.

V. Final Measurements and Evaluations

```
% Voltage to Corrected Force
messured_voltage = 2.92;  %volatge output in O-scope
force_N = voltage_to_force(messured_voltage);
fprintf('At %.4f V, the force is %.4f N\n', example_voltage, example_force_N);

At 2.9200 V, the force is 277.3969 N
```

Figure 6: The direct output from Matlab script where the voltage measured was inputted to calculate the force.

Using the described system, a female volunteer was asked to exert grip force on the mechanism. The measured output voltage was 2.92 V. Substituting this value into the final force equation resulted in a computed grip force of around 277.4 N. According to published ergonomic data, the average grip strength for females is approximately 292 N. Given the inherent biological variability and potential slight measurement offsets, our result falls well within a reasonable and expected range. This supports both the reliability of our sensor calibration and the accuracy of our instrumentation design.

In conclusion, the sensor system accurately measured grip strength through a well-designed circuit that carefully considered gain, frequency response, and calibration. The output values demonstrate the device's effectiveness in converting small strains into usable, reliable physical measurements.