UNIVERSITY OF PRINCE EDWARD ISLAND

# Building and Testing an Amplified Strain Gage Circuit Lab #4

## ENGN 3220: Engineering Measurements

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**12/6/2019**

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# 1. Introduction

This report outlines the design, build, troubleshooting and testing of an amplified strain gage circuit device. It covers the functioning properties of instrumentation amplifier gain as well as strain gage measurements. The lab provided this through the design and fabrication of a half bridge strain gage circuit, a three op-amp instrumentation amplifier and the physical application of strain gages to measure strain within a bending piece of steel. Various methods of reading and displaying the varying voltage output from the amplified strain gage circuit where utilised, including a digital multimeter, oscilloscope and an Arduino Nano with serial monitor and graphical waveform display. The design of the circuits and the process of selecting components was also discussed throughout this report.

<u>The following relevant equations will be used through this report:</u>

$$Voltage\ Divider:\ V_{out} = V_{in}\left(\frac{R_2}{R_1 + R_2 + R_3}\right)$$

$$Average = \frac{Sum\ of\ a\ data\ set}{Sample\ size}$$

$$Force\ = F\ = ma$$

$$Strain\ on\ beam\ = \varepsilon\ = \frac{\Delta V}{KVG_F}$$

$$Stress\ on\ beam\ = \sigma = \frac{6WL}{BT^2}$$

# 2. Materials and Equipment

- 2 x strain gages (Omega SGD-3/120-LY11)
- 2 x 120 Ω resistors
- 2 x 5 KΩ 20-turn trimmer potentiometers (89PR5K)
- Various 22-gauge jumper wires
- A piece of steel for measuring strain (1/8” thick by 1.5” wide by 36” long in this case)
- Strain gage glue (or super glue)
- Electrical tape
- Electronics solder wire
- Soldering Breadboard
- Prototyping breadboard
- 1 x Arduino Nano

- 1 x micro USB cable (for Arduino)
- Multimeter (Amprobe AM-530)
- DC power supply (Gw Instek GPS-3030D)
- Soldering Station (Apex Tool Group Weller WES51)
- 1 x 6-inch C-Type Clamp (Mastercraft)
- 1 x 1.0 kg calibration weight
- 1 x 0.4 kg calibration weight

**Instrumentation Amplifier Materials:**

- 1 x LM324 Quad Op-amp (Texas Instruments)
- 1 x 0.1 $\mu$F non-polarized capacitor
- 1 x 2.0 kΩ resistor
- 2 x 39 kΩ resistors
- 2 x 47 kΩ resistors
- 2 x 1.0 MΩ resistors

  For the test input voltage divider:
  - 1 x 22 Ω resistor
  - 2 x 100 kΩ resistor

## 3. Procedure

This lab was composed of two main parts, developing a three op-amp instrumentation amplifier as well as building a device to measure strain in a piece of steel, using strain gages and a Wheatstone bridge circuit.

### Instrumentation Amplifier

The first part of the lab involved the design, build and testing of an instrumentation amplifier. This circuit, which can be seen in figure 4, was designed using appropriate resistors to provide a gain of approximately 800 (calculations shown in results). The first stage of the amplifier was built on a prototyping breadboard as can be seen in the following figure. A voltage divider circuit was connected to the two positive inputs of both op-amps to provide an input signal of 0.5 mV. This circuit was tested, using a multimeter measuring voltage at Vout, with resistors for R1, R2 and R5 to provide a desired gain. The values for these resistors and gain calculation can be seen in the results section.

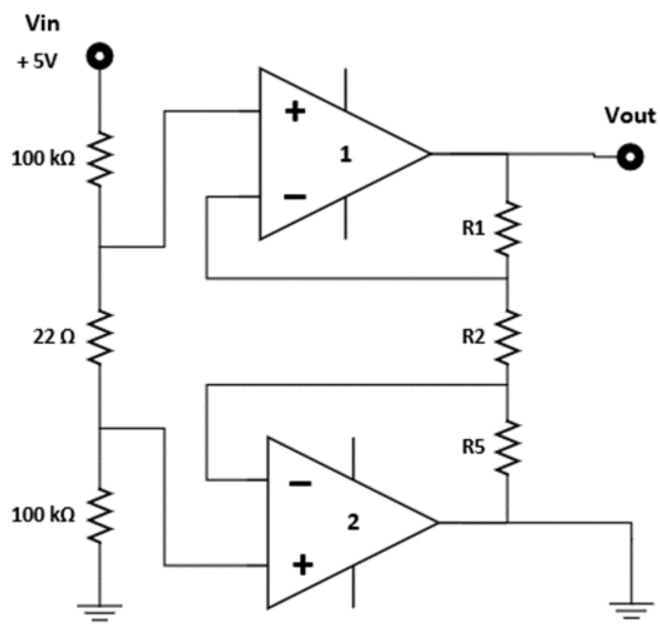


**Figure 1: First Stage amplifier test circuit wiring diagram**

Once the first stage of the amplifier was confirmed to be functioning, the second stage of the instrumentation amplifier was built. This second stage can be seen in the following figure. The same voltage divider circuit was used and connected in the circuit, as shown to provide an input signal of 0.5 mV. This circuit was tested, using a multimeter measuring voltage at Vout, with resistors for R3, R4, R6 and R7 to provide a desired gain. The values for these resistors and gain calculation can be seen in the results section.

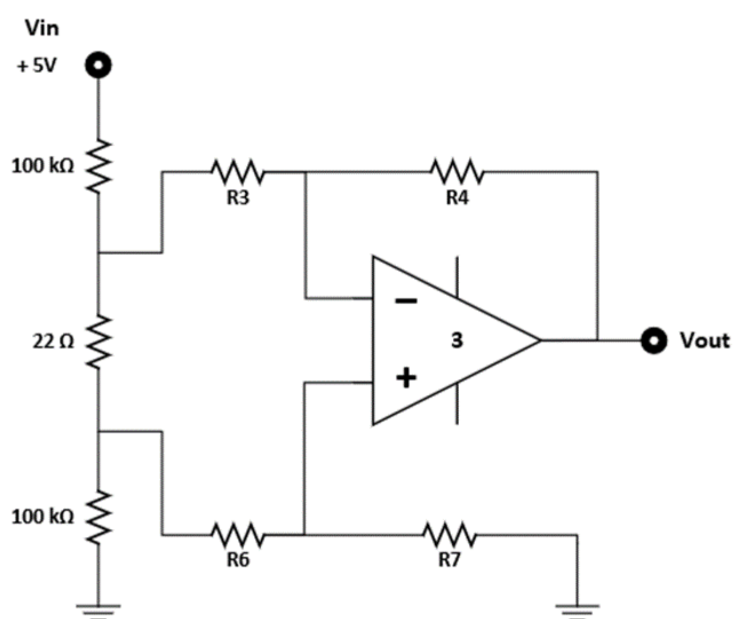


**Figure 2: Second stage amplifier test circuit wiring diagram**

Once the second stage of the amplifier was confirmed to be functioning, both the first and second stage amplification circuits where combined to form a complete instrumentation amplifier. This instrumentation amplifier can be seen in the following figure. Once again, a voltage divider circuit was connected to the two positive inputs of op-amps 1 and 2 to provide an input signal of 0.5 mV. This instrumentation amplifier was tested, using a multimeter measuring voltage at Vout, to ensure the expected amount of gain was being developed. The total gain calculations for the amplifier can be seen in the results section.

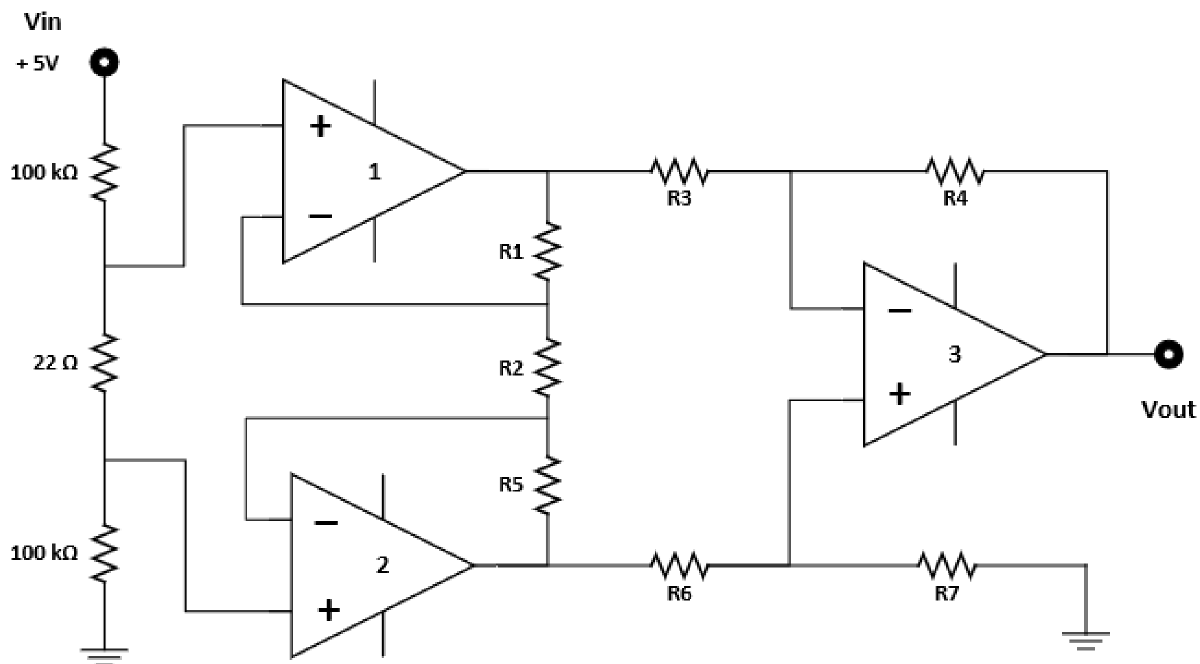


**Figure 3: Complete instrumentation amplifier test circuit wiring diagram**

The following figure shows the completed instrumentation amplifier wiring diagram. Connection points V1 and V2 are the input locations for the strain gage circuit. This circuit was then transferred from the prototyping breadboard onto a soldering breadboard.

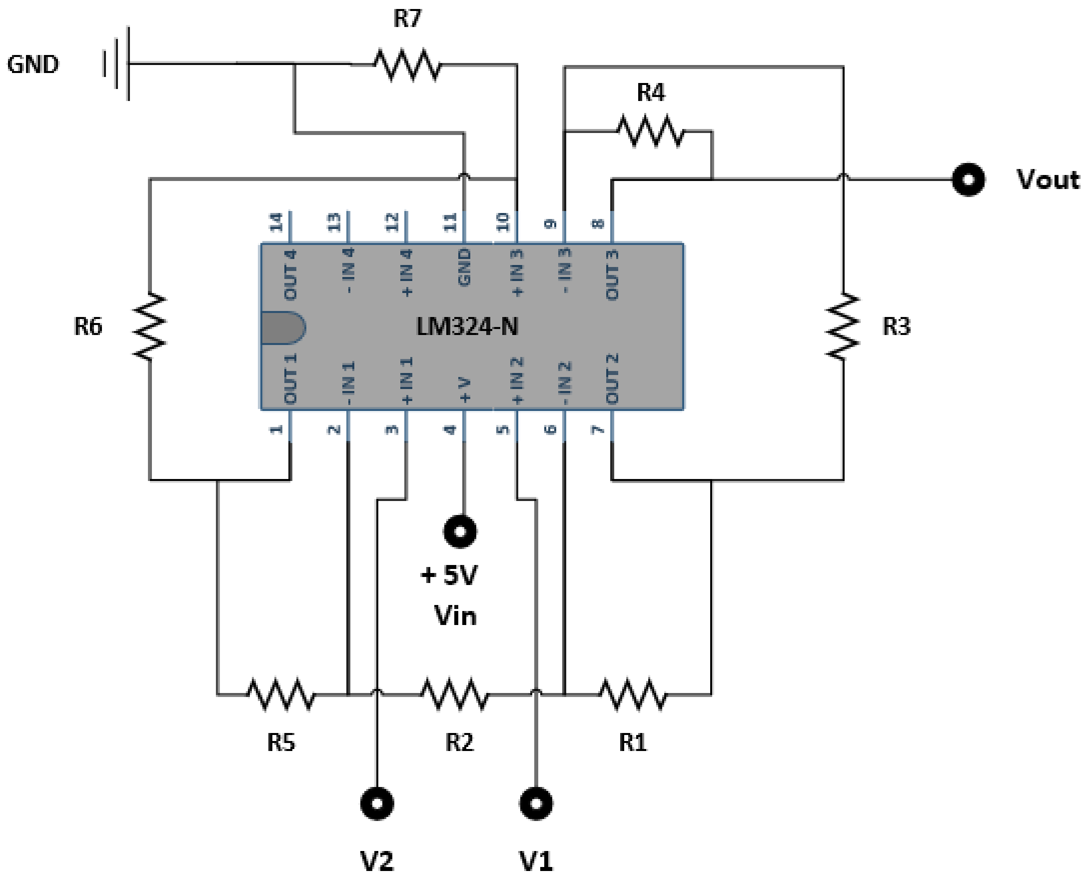


**Figure 4: Complete instrumentation amplifier circuit wiring diagram**

## Strain Gages and Wheatstone Bridge Circuit

Once the instrumentation amplifier circuit was built, tested and confirmed to be functioning, the second part of the lab began. This part of the lab started with the attachment of two strain gages to a piece of steel. The steel was grounded down and sanded to provide a smooth finish to mount the gages onto. Once the surface was clean, glue was applied to the metal and the strain gages where fixed to the surface. Once the glue dried it was time to solder wires onto the strain gage leads. Once the wires where soldered, the leads where insulated by wrapping electrical tape around the steel. The wires where then secured onto the steel with tape as well, so that the delicate leads on the stain gages would not be torn off. The strain gages and wire leads were attached onto the steel piece, as depicted in the following diagram.

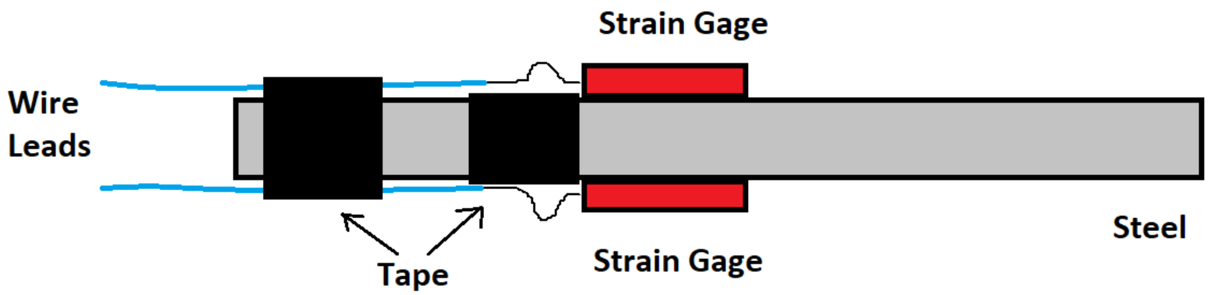


**Figure 5: Strain gages and wire leads fastened onto the steel**

The next part in the process was building the half bridge Wheatstone bridge circuit to read the strain gage measurements. The first step was to determine the resistance of the strain gages by measuring them with a multimeter. It was determined that we were using 120Ω gages. From here two 120Ω resistors were collected and measured to ensure that they where as accurate as possible. Two 5KΩ trimming potentiometers were also collected for use in balancing the bridge. This balancing was necessary to ensure that both resistances were identical, so that an accurate strain measurement could be achieved. Once all the components were collected, a circuit depicted below was built on a prototyping breadboard.

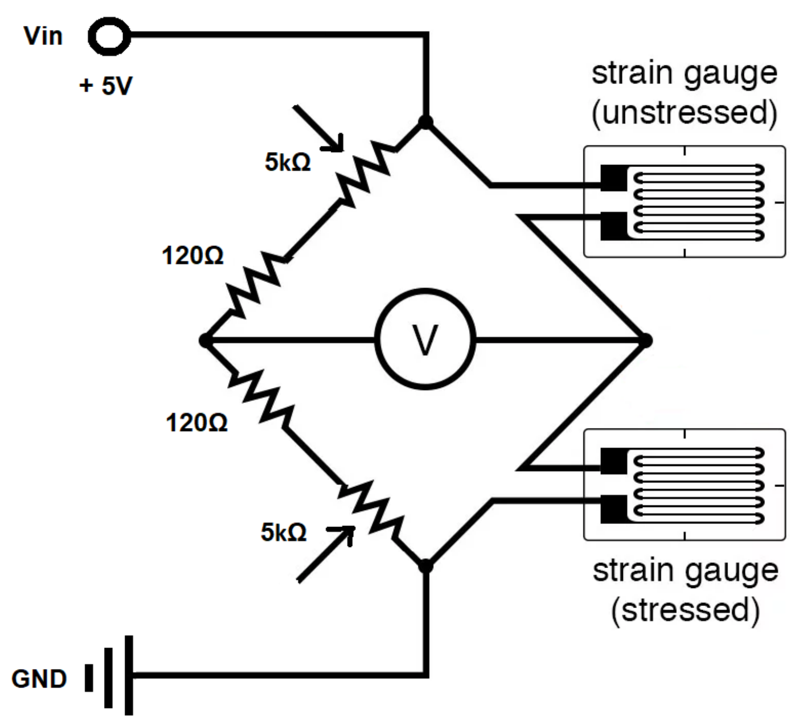


**Figure 6: Half bridge Wheatstone bridge circuit**

A multimeter was connected in the middle of the bridge to measure the voltage change when bending the steel. Once the circuit was tested and fully functioning on the breadboard, it was now possible to transfer the bridge circuit onto the soldering breadboard with the instrumentation amplifier circuit. A multimeter was first used to verify the functionality and read the varying output voltage of the amplified strain gage circuit. Afterwards, an Arduino Nano was soldered onto the breadboard to read the output of the circuit. A programming code was used to display the voltage and waveform onto the serial monitor. The code for the Arduino can be seen in Appendix A and B. The following figure shows the complete circuit connections including the instrumentation amplifier, Wheatstone bridge circuit and the Arduino Nano.

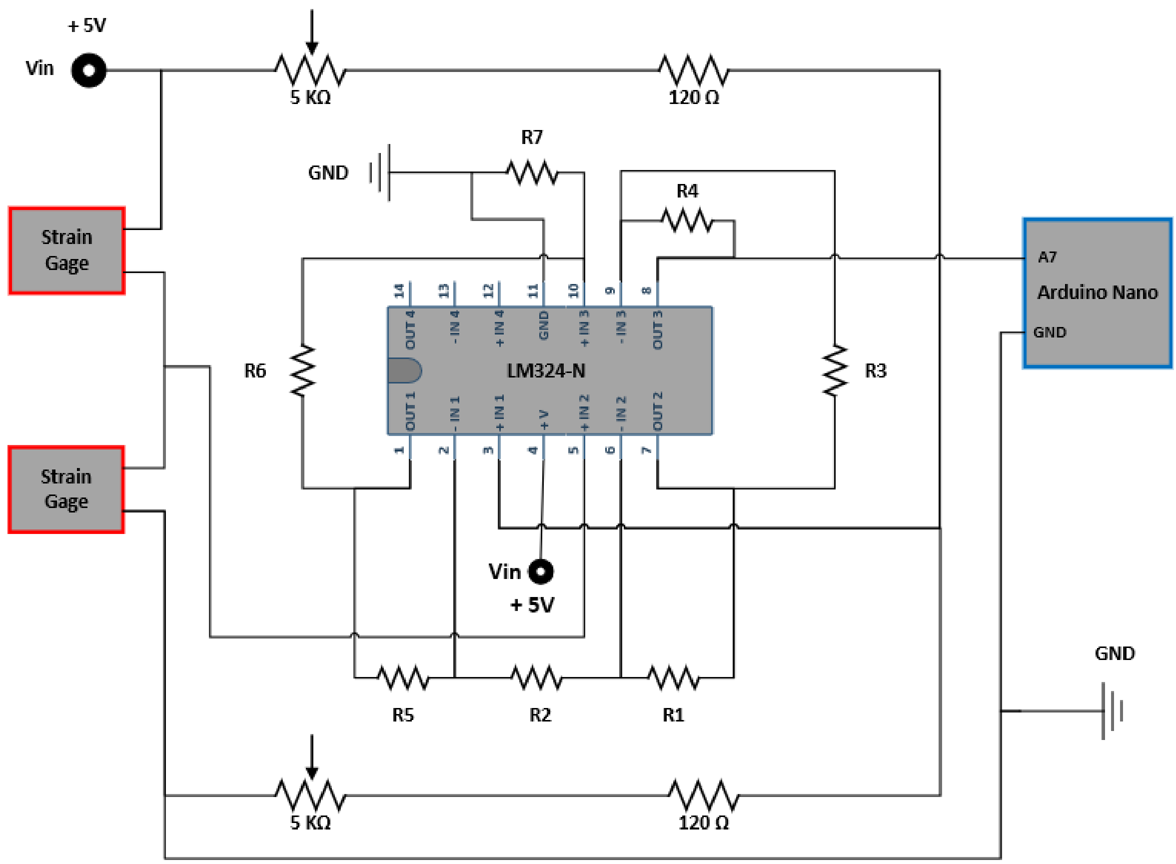


**Figure 7: Complete amplified strain gage measuring circuit**

## Strain Gage Circuit Testing

Once the complete instrumentation amplifier and strain gage circuit was confirmed to be functioning, a test scenario could be set up. This set up can be seen in the following figure. The piece of steel with the gages was secured with a C-clamp to the top of a table following the dimensions shown in the diagram. The strain gages where connected to the circuit, (which was powered from a DC power supply) and the Arduino was plugged into the computer which read the voltage output from the strain gages. The voltage output was also being measured by a multimeter to compare values. The calibration weights of 1.4 kg and 1 kg where suspended off of the end of the steel beam. Voltage output measurements where recorded with these weights hanging as well as with no weight hanging. These values can be seen in the following measurements and results section. Pictures of this set up and device can be seen in Appendix D.

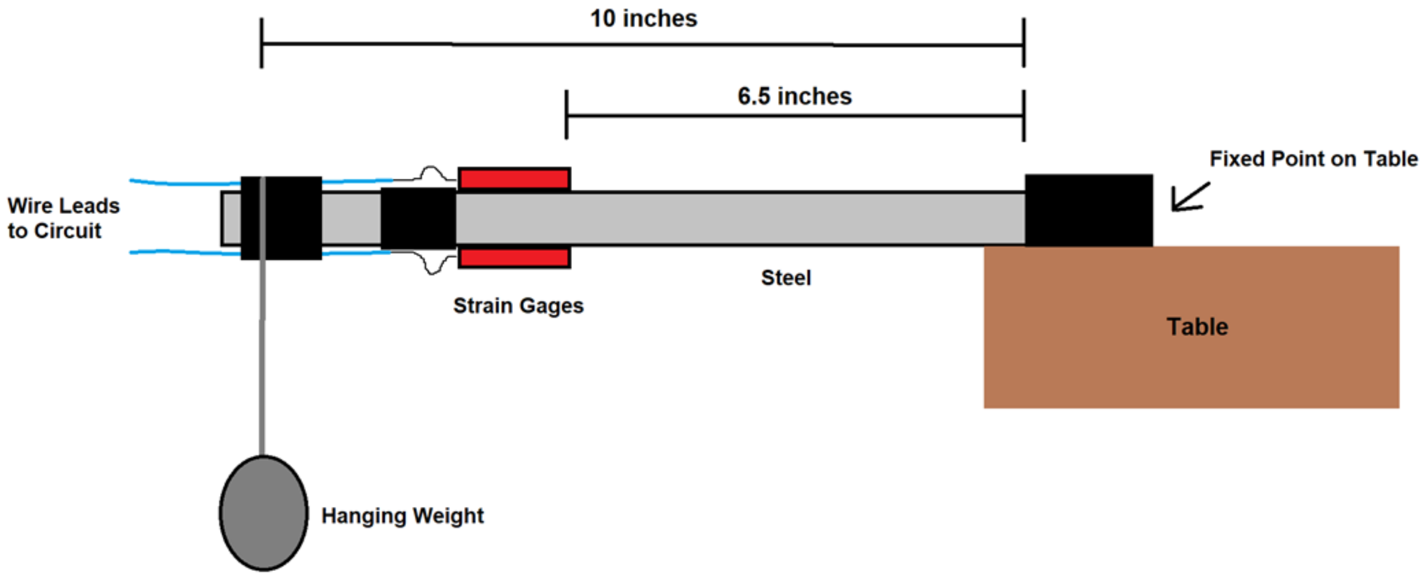


**Figure 8: Strain gage test set up**

# 4. Measurements and Results

## Instrumentation Amplifier

For the instrumentation amplifier circuit, a gain of 800 to 1000 was required to increase the small millivolt output from the Wheatstone bridge circuit to a larger voltage output. For this to occur, gain resistor values for the circuit needed to be calculated. The gain of the first stage of the amplifier would be multiplied by the gain of the second stage amplifier to give an overall gain. With this in mind, it was determined to use a gain of approximately 40 for the first stage and approximately 20 for the second stage. The gain for the first stage amplifier (figure 1) was calculated as follows:

$$Gain = 1 + \frac{2 \times R1}{R2} = 1 + \frac{2 \times 39000}{2000} = 39$$

From this calculation, R1 = 39 kΩ and R2 = 2.0 kΩ. Since R1 and R5 are equal, R5 = 39 kΩ. The gain for the second stage amplifier (figure 2) was calculated as follows:

$$Gain = \frac{R4}{R3} = \frac{1000000}{47000} \approx 21$$

From this calculation, R4 = 1 MΩ and R3 = 47 kΩ. Since R4 and R7 are equal, R7 = 1 MΩ. Since R3 and R6 are equal, R6 = 47 kΩ. The overall gain of the instrumentation amplifier was calculated as follows:

$$Total\ Gain = First\ Stage \times Second\ Stage = \ 39 \times 21 = 820$$

The calculations for the voltage divider input circuit (built for gain value testing), can be seen as follows:

$$V_{out} = \frac{5V \times 22\Omega}{(100000\Omega + 100000\Omega + 22\Omega)} = 0.00054V \ \approx 0.5\ mV$$

The results from the first and second stage amplifier testing, as well as the complete instrumentation amplifier on the prototyping breadboard and soldering board testing can be seen in the following tables. The resistance and voltage values where measured using a multimeter. The input voltage Vin, originated from the voltage divider test circuit that was built. The Vout (shorted) values where when the voltage divider circuit was shorted to ground. This was done to check for DC voltage offset in the op-amps so it could be accounted for when calculating the gain of the circuit. The calculated gain values seen in the tables where completed above. The 'measured gain' values where based on the voltage readings measured from the circuits themselves. The calculations for the 'measured gain' can be seen below.

**First stage amplifier measured gain:**

$$Gain = \frac{V_{out} - V_{out\ shorted}}{V_{in}} = \frac{13mV - (-9.7mV)}{0.5mV} = 45.4$$

**Second stage amplifier measured gain:**

$$Gain = \frac{V_{out} - V_{out\ shorted}}{V_{in}} = \frac{30.4mV - 16.4mV}{0.5mV} = 28$$

**Complete instrumentation amplifier (on prototype board) measured gain:**

$$Gain = \frac{V_{out} - V_{out\ shorted}}{V_{in}} = \frac{748mV - 228.8mV}{0.5mV} = 1038.4$$

**Complete instrumentation amplifier (on soldering board) measured gain:**

$$Gain = \frac{V_{out} - V_{out\,shorted}}{V_{in}} = \frac{640mV - 161mV}{0.5mV} = 958$$

| First Stage Amplifier Circuit | | | | | | | |
|---|---|---|---|---|---|---|---|
| Resistances (kohms) | | | Input Voltage | Vout (shorted) | Vout | Calculated Gain | Measured Gain |
| R1 | R5 | R2 | | | | | |
| 38.46 | 38.47 | 1.96 | 0.5 mV | -9.7 mV | 13 mV | 39 | 45 |

**Figure 9: First stage amplifier circuit test results**

| Second Stage Amplifier Circuit | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Resistances (kohms) | | | | Input Voltage | Vout (shorted) | Vout | Calculated Gain | Measured Gain |
| R3 | R6 | R4 | R7 | | | | | |
| 46.5 | 46.4 | 992 | 999 | 0.5 mV | 16.4 mV | 30.4 mV | 21 | 28 |

**Figure 10: Second stage amplifier circuit test results**

| Breadboard Instrumentation Amplifier Circuit | | | | |
|---|---|---|---|---|
| Input Voltage | Vout (shorted) | Vout | Calculated Gain | Measured Gain |
| 0.5 mV | 228.8 mV | 748 mV | 820 | 1038 |

**Figure 11: Complete instrumentation amplifier (on prototyping board) test results**

| Solder Board Instrumentation Amplifier Circuit | | | | |
|---|---|---|---|---|
| Input Voltage | Vout (shorted) | Vout | Calculated Gain | Measured Gain |
| 0.5 mV | 161 mV | 640 mV | 820 | 958 |

**Figure 12:Complete instrumentation amplifier (on soldering board) test results**

## Amplified Half Bridge Strain Gage Circuit Testing

A functioning strain gage measurement circuit was achieved by the end of the lab. When in a state of no strain, the output voltage was adjusted, using the trim pots, to produce approximately 2.37 volts. When a bending force was applied in one direction, the output voltage would increase. When the steel was bent in the other direction, the voltage output would decrease. These changing values where verified by using the Arduino code to display the output waveform as well as display the voltage output values as analog readings.

From this point the strain gage circuit testing, outlined in the procedure took place. The measurement results from the test scenarios can be seen in the following table. The Arduino analog readings where averaged and then converted to voltage values. The output voltage was also measured with a multimeter for comparison.

| Test Loads (mass) | | | | | |
|---|---|---|---|---|---|
| 1.4 kg | | 1 kg | | 0 kg | |
| Analog Readings | Vout (multimeter) | Analog Readings | Vout (multimeter) | Analog Readings | Vout (multimeter) |
| 293 | 1.41 V | 354 | 1.70 V | 487 | 2.35 V |
| 292 | | 352 | | 485 | |
| 292 | | 352 | | 486 | |
| 291 | | 353 | | 486 | |
| 293 | | 351 | | 486 | |
| 294 | | 351 | | 486 | |
| 292 | | 353 | | 485 | |
| 292 | | 352 | | 482 | |
| 292 | | 347 | | 483 | |
| 292 | | 352 | | 481 | |
| Average | Vout (arduino) | Average | Vout (arduino) | Average | Vout (arduino) |
| 292.3 | 1.43 | 351.7 | 1.72 | 484.7 | 2.37 |

**Figure 13: Output voltage calibration test data**

Using this data as well as the length/distance values collected from the test set up, the calculations for weight of load, stress and strain where accomplished. These results are outlined in the table below. The calculations for these results can be seen in Appendix C: Strain Gage Circuit Testing Calculations.

| Mass (kg) | Weight (N) | Vout (Vdc) | Stress (Mpa) | Strain |
|---|---|---|---|---|
| 1.4 | 13.73 | 1.43 | 19.07 | 0.714 |
| 1 | 9.81 | 1.72 | 13.62 | 0.656 |
| 0 | 0 | 2.37 | 0 | 0.526 |

**Figure 14: Results from strain gage testing**

It can be seen that the stress on the beam decreased as the weight hanging from the end decreased. It can also be seen that the strain value also decreased as the weight decreased. Both of these correlations are justifiable meaning that the gages are measuring appropriately.

# 5. Discussion

### Instrumentation Amplifier

The building of this instrumentation amplifier went through many stages and tests phases to end up with a functioning circuit. The first attempt was building the circuit in its entirety with both stages of amplification connected together. It was quickly learned that once this was unsuccessful, the more appropriate approach was to build the circuit in stages and confirm each function along the way. It was too difficult to calculate the total gain of the circuit as a whole because factors of DC voltage offset and variance in individual gains where unknown. As was previously mentioned, a voltage divider circuit was built with two 1.0 MΩ and one 22 Ω resistors to produce a known input to the circuits of 0.5mV. This allowed for a consistent input voltage for all tests of each stage of the amplifier. Using this as a reference point for voltage output, the gain of each stage of the amplifier could be determined. The measurements of voltage output where taken with the voltage divider set up as normal as well as with the voltage divider shorted to ground. With the voltage divider shorted to ground, this allowed us to measure the DC offset voltage of the op-amp, which we could subtract from the voltage measured without the short in place. This DC voltage offset was believed to be due to the precision of the gain resistors being too far off. In the design of this amplifier, it was very crucial that the resistors where close to the stated values. To improve upon this issue, many resistors where measured from the available bins to find resistors with measured values very close to one another. With the precise resistors, the DC offset was improved but still not eliminated completely. It was concluded that this offset was an issue inside the chip, and the further gain calculations subtracted out this offset. This method of building resulted in attaining an appropriate gain from the first and second stage amplifiers. The use of the voltage divider and shorting was also used when the amplifier stages where combined. The DC offset was measured and the final gain of the instrumentation amplifier was measured successfully.

Another issue that was noticed during testing was that some of the finer wired components would sporadically not make a consistent connection in the prototyping breadboard. This issue was especially noticed when transferring the completed instrumentation amplifier from the prototyping breadboard to the soldering breadboard without changing any other components. This more stable arrangement decreased the overall gain from a measured 1038 to 958, making it closer to the expected calculated gain of 820. Although closer, the gain was still higher than expected, likely due to the slight variance in resistor values. This higher gain value was still within the desired range, so the instrumentation was incorporated into the strain gage circuit.

### Amplified Half Bridge Strain Gage Circuit

As was previously mentioned, a functioning half bridge strain gage measuring device was built. In the half bridge circuit, one gage is compressed when the other gage is stretched and vice versa. This meant that both gages respond to strain, allowing the bridge to be more responsive to forces applied. Both strain gages increase or decrease resistance by the same proportional quantity.

During the building process, there were a few problems that were encountered. First off, it was determined the 120Ω resistors where not accurate enough alone to produce a balanced bridge circuit. It was attempted to solve this problem by placing a 10 kΩ potentiometer in series with both 120Ω resistors. This did not solve the problem, since these potentiometers where also not adequately precise to match the resistances. It was then decided to use 5 kΩ 20-turn trimming potentiometers in series with the 120Ω resistors. This solved the output voltage problem, by allowing us to accurately equalize the resistances in the bridge.

Another problem that was encountered during the building and testing process was that we noticed an intermitted short with the leads of the strain gages to the piece of steel. This issue was resolved by using tape to isolate the leads of the gages from the steel beam.

## 6. Conclusions

This lab tested our abilities to design, build, troubleshoot and test an instrumentation amplifier as well as a strain gage half bridge circuit. The functioning properties of amplifier gain as well as strain gage measurements where developed through the fabrication of the strain gage circuit, three op-amp instrumentation amplifier and the physical application of the gages to a bending piece of steel. The combination of the two circuits on a soldering breadboard as well as the physical application of the strain gages to a steel beam where effectively accomplished. In the end, a successful amplified strain gage measurement circuit was built measuring the strain and stress, through varying output voltage, of a bending piece of steel.

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## Appendix A: Arduino Code for Strain Gage Waveform Display

```
int sensorPin = A7;    // select the input pin for the potentiometer
int ledPin = A1;      // select the pin for the LED
int sensorValue = 0;  // variable to store the value coming from the sensor
int interval = 1000;  // microseconds between samples

void setup()
{
  pinMode(ledPin, OUTPUT);        // declare the ledPin as an output
  Serial.begin(9600);       // this sets the baud rate, which is the comm speed, 9600 bits/sec
  Serial.println("measurements class demo");
  Serial.println("==========================================");
}

void loop()
{
  // read the value from the sensor:
  // turn the ledPin on
  digitalWrite(ledPin, HIGH);
  // stop the program for <sensorValue> milliseconds:
  delayMicroseconds(300);
  sensorValue = analogRead(sensorPin);
  Serial.print(400);
  Serial.print(",   ");
  Serial.print(sensorValue);
  Serial.print(",   ");
  Serial.println(600);
  // turn the ledPin on
  digitalWrite(ledPin, LOW);
  // stop the program for <sensorValue> milliseconds:
  delayMicroseconds(interval);
  // turn the ledPin off:
  //digitalWrite(ledPin, LOW);
   delay(interval);    // stop the program for <sensorValue> milliseconds:
}
```

## Appendix B: Arduino Code for Strain Gage Voltage Output

```
int sensorPin = A7;    // select the input pin for the potentiometer
int sensorValue = 0;  // variable to store the value coming from the sensor
int interval = 200;  // microseconds between samples

void setup()
{
  Serial.begin(9600);  // this sets the baud rate, which is the comm speed, 9600 bits/sec
 }

void loop()
{
  // stop the program for sensorValue milliseconds:
  delayMicroseconds(interval);
  sensorValue = analogRead(sensorPin);
  Serial.println(sensorValue);
  // stop the program for sensorValue milliseconds:
  delayMicroseconds(interval);
}
```

# Appendix C: Strain Gage Circuit Testing Calculations

## Calculations for weight (load) at test points:

$$F = ma = 1.4\,kg \times 9.81\,{}^{m}/{}_{s^2} = 13.73\,N = weight$$

$$F = ma = 1.0\,kg \times 9.81\,{}^{m}/{}_{s^2} = 9.81\,N = weight$$

## Strain Calculations:

| | Test loads | | |
|---|---|---|---|
| | **1.4 kg** | **1 kg** | **0 kg** |
| **Vout** | 1.43 V | 1.72 V | 2.37 V |

$$\varepsilon = \frac{\Delta V}{KVG_F}$$

Where, ΔV = Voltage output difference (V)
K = ½ for a half bridge circuit
V = Supply voltage (V)
$G_F$= 2 for gage factor in most metallic strain gages

Strain with 1.4 kg load: $\varepsilon = \frac{(5-1.43)}{0.5\times5\times2} = 0.714$

Strain with 1.0kg load: $\varepsilon = \frac{(5-1.72)}{0.5\times5\times2} = 0.656$

Strain with 0 kg load $\varepsilon = \frac{(5-2.37)}{0.5\times5\times2} = 0.526$

## Stress Calculations:

| Distance Values | Conversions | |
|---|---|---|
| L | 3.5 inch | 0.0889 m |
| B | 1.5 inch | 0.0381 m |
| T | 1/8 inch | 0.003175 m |

$$\sigma = \frac{6WL}{BT^2}$$

Where, W = Applied force (load on beam) (N)
L = Distance between the load and strain gages (m)
B = Width of beam (m)
T = Thickness of beam (m)

Stress with 1.4 kg load: $\sigma = \frac{6(13.73N)(0.0889m)}{(0.0381m)(0.003175m)^2} = 19068262\ {}^{N}/{}_{m^2} = 19.07\ MPa$

Stress with 1.0 kg load: $\sigma = \frac{6(9.81N)(0.0889m)}{(0.0381m)(0.003175m)^2} = 13624155\ {}^{N}/{}_{m^2} = 13.62\ MPa$

Stress with 0 kg load: $\sigma = \frac{6(0N)(0.0889m)}{(0.0381m)(0.003175m)^2} = 0\ {}^{N}/{}_{m^2} = 0\ MPa$

## Appendix D: Pictures