Strain Gauges

GT Off-Road Racing | Data Acquisition

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Table of Contents

[1.0 Overview 2](#_Toc96450793)

[1.1 Introduction 2](#_Toc96450794)

[1.2 Point of Contact 2](#_Toc96450795)

[2.0 Strain Gauges 3](#_Toc96450796)

[2.1 Strain Gauge Background 3](#_Toc96450797)

[3.0 Wheatstone Bridge 4](#_Toc96450798)

[3.1 Wheatstone Bridge Circuit 4](#_Toc96450799)

[3.1.1 Circuit Derivation 4](#_Toc96450800)

[3.1.2 Swapping Resistors For Strain Gauges 4](#_Toc96450801)

[3.2 Wheatstone Bridge Configurations 4](#_Toc96450802)

[3.2.1 Quarter-Bridge Strain Gauge Input 5](#_Toc96450803)

[3.2.2 Half-Bridge Strain Gauge Input 5](#_Toc96450804)

[3.2.3 Full-Bridge Strain Gauge Input 5](#_Toc96450805)

[4.0 Hardware Reference 6](#_Toc96450806)

[4.1 Schematic (Input) 6](#_Toc96450807)

[4.1.1 Quarter-Bridge Strain Gauge Configuration 6](#_Toc96450808)

[4.1.2 Half-Bridge Strain Gauge Configuration 6](#_Toc96450809)

[4.1.3 Full-Bridge Strain Gauge Configuration 6](#_Toc96450810)

[4.1.4 Calibration 6](#_Toc96450811)

[4.2 Schematic (Output) 7](#_Toc96450812)

[4.3 PCB 8](#_Toc96450813)

[4.3.1 Single Strain Gauge Input, Voltage Output 8](#_Toc96450814)

[4.3.2 Single Strain Gauge Input, Full-Bridge Output 9](#_Toc96450815)

[4.3.3 Load Cell Input, Voltage Output 9](#_Toc96450816)

[4.4 Wiring 9](#_Toc96450817)

[5.0 Software Theory Of Operation 10](#_Toc96450818)

[5.1 Amplification Calculations 10](#_Toc96450819)

[5.1.1 SGT-3N/350-TY11 Strain Gauge (Quarter-Bridge) 11](#_Toc96450820)

[5.2 Calibration Routine 12](#_Toc96450821)

[6.0 References 13](#_Toc96450822)

[6.1 YouTube Videos 13](#_Toc96450823)

[6.2 Websites 13](#_Toc96450824)

[7.0 Revision History 14](#_Toc96450825)

# Overview

## Introduction

## Point of Contact

Andrew Hellrigel ([ahellrigel3@gatech.edu](mailto:ahellrigel3@gatech.edu)): Designed PCB for load cells

# Strain Gauges

## Strain Gauge Background

A strain gauge is an electromechanical device that changes in resistance when a strain is applied. When an external force is applied on an object, strain (tensile/compressive deformation in the shape of the object) occurs. Strain is defined as the change in length divided by the original length.

|  |  |
| --- | --- |
| bonded strain gauge  Figure Forces measured by strain gauge | What is a Strain Gauge and How Does it Work? • Michigan Scientific  Figure Strain gauge bonded to a test specimen |

A strain gauges can be bonded to a test specimen (e.g. chassis tube). When the mechanical element has a force applied, the resulting strain can be measured at a specific point on the mechanical element.

|  |  |  |
| --- | --- | --- |
| Diagram, engineering drawing  Description automatically generated  Figure S-type load cell 3D model | How Does a Strain Gauge Load Cell Work? | Load Cell Central  Figure Forces measured by S-type load cell | Load Cell Amplifier HX711 Breakout Hookup Guide - learn.sparkfun.com  Figure S-type load cell mounted |

A load cell is a transducer that measures force, and outputs this force as an electrical signal. For example, the S-type load cell pictured above measures tension and compression forces and can be mounted using the two threaded mounting holes on the top and bottom horizontals of the S.

# Wheatstone Bridge

## Wheatstone Bridge Circuit

### Circuit Derivation

Diagram, schematic

Description automatically generated

Figure Wheatstone Bridge Circuit

A Wheatstone bridge is comprised of two voltage dividers in parallel. As such, the formulae for the node voltages are as follows:

and are derived from the voltage divider formula. is the voltage difference between the A+ and A- nodes. is proportional to the resistance variation of the resistors, R1, R2, R3, and R4. For example, if R1=R2=R3=R4, then VA+=VA-. As a result, Vout = 0. When the value of any resistor is changed, then the voltage difference Vout will change.

### Swapping Resistors For Strain Gauges

The components for R1, R2, R3, and R4 can be normal resistors, or can be selectively replaced by a strain gauge (variable resistor based on strain). Using a strain gauge will allow Vout to increase/decrease based on the amount of strain on the test specimen.

## Wheatstone Bridge Configurations

Table Wheatstone Bridge Configurations

|  |  |  |
| --- | --- | --- |
| Configuration | Number of strain gauges | Number of resistors |
| Quarter-bridge | 1 | 3 |
| Half-bridge | 2 | 2 |
| Full-bridge | 4 | 0 |

### Quarter-Bridge Strain Gauge Input

A quarter bridge strain gauge input is the simplest configuration that can be used. The resistive strain gauge is attached to the inputs on connector J1 to pins 5V and A+, and R1 is omitted from the PCB assembly. R2-R4 will be added to the PCB to complete the strain gauge.

### Half-Bridge Strain Gauge Input

A half bridge strain gauge can also be connected to this circuit. The main advantage of a half-bridge strain gauges is that it compensates for changes in temperature.

### Full-Bridge Strain Gauge Input

By omitting R1-R4, a full-bridge strain gauge can be connected directly to this circuit (this is the case for standard load cells that buy from Omega).

https://www.transducertechniques.com/wheatstone-bridge.aspx

# Hardware Reference

## Schematic (Input)

Diagram, schematic

Description automatically generated

Figure

The above section of the schematic is the input along with the Wheatstone bridge. A Wheatstone bridge is a circuit that converts a change in resistance to a differential change in voltage between A+ and A-. R1-R4 are the bridge completion resistors.

### Quarter-Bridge Strain Gauge Configuration

Attach a resistive strain gauge to the input pins, 5V and A+, on connector J1 to pins 5V and A+, and R1 is omitted from the PCB assembly. R2-R4 will be added to the PCB to complete the strain gauge.

### Half-Bridge Strain Gauge Configuration

A half bridge strain gauge can also be connected to this circuit. The main advantage of a half-bridge strain gauges is that it compensates for changes in temperature.

### Full-Bridge Strain Gauge Configuration

By omitting R1-R4, a full-bridge strain gauge can be connected directly to this circuit (this is the case for standard load cells that buy from Omega).

### Output Signal Gain

R9 is the gain setting resistor for the amplifier. This resistor used should be as exact as possible. However, fi that’s not possible, use a higher resistance as opposed to a lower resistance if the difference is equal.

### Calibration

R5-R6 are calibration resistors. When the slide switches are activated, they create a parallel voltage divider, decreasing the resistance of either R3 or R4 by a small amount. This, in effect, is emulating a change in resistance due to measured strain, however the exact change in resistance will be known. The actual change in measured strain can be divided against the expected change in measured strain to find a calibration factor that will calibrate against and variances in the tolerances of the electrical components used. Since there are two calibration resistors, this process can be done in both tension and compression.

This method of calibration is called shunt calibration, and this video does a decent job of explaining what that is. <https://www.youtube.com/watch?v=w3RPWzUlq_Y>

## Schematic (Output)

Diagram, schematic

Description automatically generated

Figure

This portion of the schematic is the output section. It includes a voltage reference along with an instrumentation amplifier for amplifying the differential voltage generated by the Wheatstone bridge.

JP1 can be used as direct connections to the Wheatstone bridge so that you can bypass the amplifier stage if you want to use an HX711 or a Qwiic Scale as the load cell amp. The J3 connector directly outputs the analog voltage after the amplifier stage that can be fed directly into an ADC.

## PCB

A screenshot of a game

Description automatically generated with medium confidence

Figure

A screenshot of a computer

Description automatically generated with low confidence

Figure

The PCB has a connection on the left for the strain gauge input and a connection on the right for the power and the voltage signal output. The PCB is configurable to many different input and output modes. The common modes it will be used in and the components that are needed for those modes are outlined below. R9 is the gain setting resistor.

### Single Strain Gauge Input, Voltage Output

This mode is useful for measuring the strain of any component (such as a chassis member). If the board is being wired into the aux daq unit, then it will be useful to solder on the terminal blocks (J1, J3) so that wires can be easily plugged into the board. The wires from the strain gauge will plug into the left terminal block at the 5V output and the A+ output. This will make the strain gauge R1 in the Wheatstone bridge. Bridge completion resistors will need to be used for R2-R4.

If the strain gauge amplifier is being used for a specific application, it may be desirable to plug the strain gauge amplifier board directly into the PCB for the application it is being used for. In this case, the right terminal block can be omitted, and instead, headers can be used so that it can be plugged directly into a board. JP3 is where the power input and voltage signal output can be connected to the PCB. JP2 can also be used to connect to the board, but it is recommended to wire the strain gauge into the terminal block J1. The JP2 headers in the situation will be purely used for mechanical support.

It is recommended to wire the output voltage signal into an ADS8332 ADC (this is what is used for the 2022 aux daq design).

### Single Strain Gauge Input, Full-Bridge Output

The single strain gauge input, full-bridge output configuration is what can be used to measure a single strain gauge with a load cell amp such as the Sparkfun QwiicScale or the HX711 load cell amplifier. These two load cell amps are designed to measure a load cell directly which already has a full bridge of strain gauges. However, with a single strain gauge and the amplifier board, bridge completion resistors (R2-R4) can be added so that it will behave like a load cell and a load cell amp can be used to measure it. The terminal block J1 can be added to wire in the strain gauge, and the output of the full bridge will come from JP1 and the outputs can be connected directly to a Sparkfun QwiicScale or an HX711. The colors at the output of the strain gauge amplifier board should match the color inputs for the Sparkfun QwiicScale.

### Load Cell Input, Voltage Output

This board can be used as a full bridge load cell amplifier as well. In this case, J1 can be added and the load cell can be directly wired into 5V, A+, GND, A-. Some datasheets use O+ and O- for the load cell outputs, but this is the same as A+ and A-. If this is used, then no bridge completion resistors need to be added. The J3 terminal block can be added if this will be wired into the aux daq, or like the single strain gauge input, voltage output case, if it is being used for a specific application, the JP3 and JP2 pin headers can be used so that it can be connected directly to a PCB.

## Wiring

# Software Theory Of Operation

## Amplification Calculations

There are 2 distinct stages for strain gauge / load cell measurements. The first is the Wheatstone bridge where the change in resistance of the Wheatstone bridge is converted to a differential voltage that can be amplified and then measured. The general strain gauge video <https://www.youtube.com/watch?v=lWFiKMSB_4M> does a good job of explaining how this works.

For load cells, this conversion is given in the data sheet. It is generally called the full scale voltage output or electrical output and it is a gain factor given as a certain number of mV/V. So for example, given this 500lb load cell from Omega, <https://www.omega.com/en-us/force-strain-measurement/load-cells/p/LC103B>, it gives the electrical output at 3mV/V. For the amplification board the input voltage is 5V, which means over the full-scale range of the output it will go from -15mV to 15mV (since it measures in both tension and compression). Since it measures from -500lbs to 500lbs a simple division can give us the conversion factor of 33.3lbs/mV. This means that for every 33.3lbs that is applied to the load cell, the difference in the output voltage (between A+ and A-) will change by 1mV.

The REF pin of the AD8221 instrumentation amplifier offsets the output by 2.5V so that the output never goes negative. If an exact resistor for cannot be obtained, try to use a resistor with a slightly larger resistance to keep the max/min force values within the voltage measuring range.

For strain gauges, this calculation is a little bit more complex. Strain gauges have two important values in the datasheet, the resistance and the gauge factor. The first seven pages of this manual, <http://elektron.pol.lublin.pl/elekp/ap_notes/ni_an078_strain_gauge_meas.pdf>, outline the calculations that can be used to calculate the voltage gain with respect to applied strain.

|  |  |
| --- | --- |
| **Formula** | **Description** |
|  | Gauge factor |
|  | Fractional change in resistance |
|  | Strain (fractional change in length) |
|  | Strain gauge resistance |
|  | Bridge completion resistor resistance |
|  | Amplifier gain setting resistor resistance |
|  | Excitation/source voltage |
|  | Load cell or strain gauge electrical output ratio |
|  | Instrumentation amplifier voltage offset |
|  | Instrumentation amplifier gain |
|  | Voltage output from strain gauge PCB |

### SGT-3N/350-TY11 Strain Gauge (Quarter-Bridge)

<https://www.omega.com/en-us/force-strain-measurement/strain-gauges/linear-strain-gauges/sgt-uniaxial/p/SGT-3N-350-TY11>

<https://www.amazon.com/DAOKI-BF350-3AA-High-Precision-Pressure-Resistance/dp/B07X87CJD8/ref=sr_1_3?dchild=1&keywords=strain+gauges&qid=1628827897&sr=8-3>

The bridge completion resistances should match the strain gauge resistance.

Starting with calculating the maximum percent change in resistance of the strain gauge based on its specifications:

Next, the maximum and minimum resistance of the strain gauge:

Next, we calculate the maximum change in the raw output voltage from the Wheatstone bridge in both compression (strain gauge at minimum resistance) and tension (strain gauge at maximum resistance). Although can be positive or negative (centered at 0V), the instrumentation amplifier automatically adds a 2.5V offset to prevent negative voltages.

,

The largest change in voltage is used to calculate the gain for the instrumentation amplifier. This gain is required to scale the raw output voltage to range from 0V to 5V to increase the resolution of the measurements measured by the ADC.

Based on the AD8221 instrumentation amplifier datasheet, the formula for calculating the gain setting resistor is:

See code in “Strain Gauges” folder to calculate these values automatically (specifically for this PCB design) in the “calc\_quarter\_bridge\_gain.m” file.

### LC103B-500 Load Cell

<https://www.omega.com/en-us/force-strain-measurement/load-cells/p/LC103B>

For this 500lb load cell from Omega, the electrical output is 3mV/V. For every 1V of the power supply voltage, the output range will increase by 3mV. For the amplification board the input voltage is 5V, which means over the full-scale range of the output it will go from -15mV to 15mV (since it measures in both tension and compression). Therefore, we must set the gain to stretch the range to 0V to 5V when offset by 2.5V.

~~Since it measures from -500lbs to 500lbs a simple division can give us the conversion factor of 33.3lbs/mV. This means that for every 33.3lbs that is applied to the load cell, the difference in the output voltage (between A+ and A-) will change by 1mV.~~

## Calibration Routine

# References

## YouTube Videos

General strain gauges - <https://www.youtube.com/watch?v=lWFiKMSB_4M>

Strain gauge installation - <https://www.youtube.com/watch?v=s4Bq8MvwbyU>

Shunt calibration - <https://www.youtube.com/watch?v=w3RPWzUlq_Y>

## Websites

Shunt calibration - <https://www.me-systeme.de/en/technology-first/strain-gauge/Shunt-calibration>

Sparkfun QwiicScale Tutorial - <https://learn.sparkfun.com/tutorials/qwiic-scale-hookup-guide?_ga=2.81344663.165771546.1634502474-1997756260.1628974791>

HX711 - <https://www.sparkfun.com/products/13879>

500 lb Load Cell from Omega - <https://www.omega.com/en-us/force-strain-measurement/load-cells/p/LC103B>

Strain gauge calculations manual - <http://elektron.pol.lublin.pl/elekp/ap_notes/ni_an078_strain_gauge_meas.pdf>

Linear Strain Gauge from Omega - <https://www.omega.com/en-us/force-strain-measurement/strain-gauges/linear-strain-gauges/sgt-uniaxial/p/SGT-3N-350-TY11>

# Revision History

2/1/2022 (Andrew Hellrigel) – Created first revision, still need to add documentation about wiring (the inputs and outputs to the board) and the calibration routine.