KWIK CIRCUIT FAQ

Spice Model for a Half Bridge Strain Gauge Sensor – by Michael Jackson

FAQ: SPICE Model for a Half Bridge Strain Gauge Sensor

Introduction

This *KWIK* (*K*now-how *W*ith *I*ntegrated *K*nowledge) Circuit application note provides a step-by-step guide to addressing a specific design challenge. For a given set of application circuit requirements, it illustrates how these are addressed using generic formulae and makes them easily scalable to other similar application requirements. This strain gauge sensor model enables SPICE simulation of the electrical properties, from physical strain used in a half bridge configuration. The SPICE model uses parameters, which characterize the physical behavior of a gauge, which translates strain into electrical voltage. Also, a typical excitation and signal conditioning circuit that can be used to demonstrate the behavior of this simple sensor SPICE model is shown.

Strain Gauge Overview

Strain is the amount of deformation of a body due to an applied force. Strain (ε) is defined as the fractional change in length, as shown in Figure 1 below.

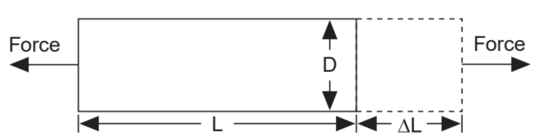

Figure 1. Definition of Strain

Strain can be positive (tensile) or negative (compressive). Although dimensionless, strain is sometimes expressed in units such as in/in or mm/mm. In practice, the magnitude of measured strain is very small. Therefore, strain is often expressed as microstrain (με), which is $\varepsilon \times 10^{-6}$. While there are several methods of measuring strain, the most common is with a strain gauge, a device whose electrical resistance varies in proportion to the amount of strain applied. The most widely used gauge is the bonded metallic strain gauge, which consists of a very fine wire or, more commonly, metallic foil arranged in a grid pattern. The grid pattern maximizes the amount of metallic wire or foil subject to strain in the parallel direction, increasing the gain for the gauge (Figure 2).

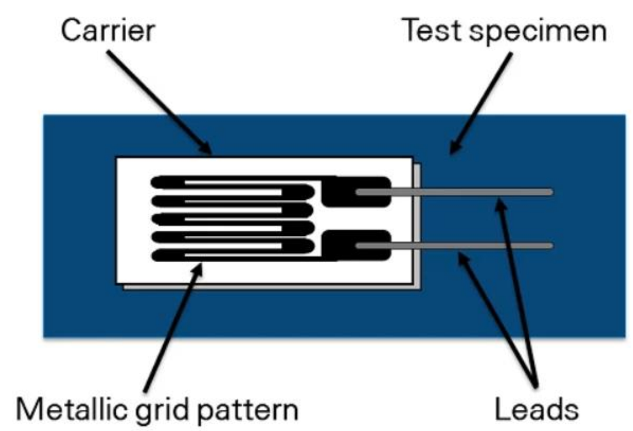

Figure 2. Bonded metallic strain gauge

The grid is bonded to a thin backing, called the carrier, which is attached directly to the test specimen. The strain experienced by the test specimen is transferred directly to the strain gauge, which responds with a linear change in electrical resistance. Strain gauges are available commercially with nominal (no strain) resistance values from 30 to 3000 Ω, with 120, 350, and 1000 Ω being the most common values.

A fundamental parameter of the strain gauge is its sensitivity to strain, expressed as the gauge factor (GF). Gauge factor is defined as the ratio of fractional change in electrical resistance to the fractional change in length (strain):

$$GF = \frac{\Delta R/R}{\Delta L/L} = \frac{\Delta R/R}{\varepsilon} \qquad \text{Eq. 1}$$

The Gauge Factor for metallic strain gauges is typically around 2. The gauge factor, maximum strain, and nominal no strain resistance are specified in the strain gauge datasheet.

Strain Gauge Bridge Operation

Real world strain measurements rarely involve quantities larger than a few millistrain ($\varepsilon \times 10^{-3}$). Therefore, measuring strain requires the accurate detection of very small changes in resistance (fractions of an Ohm). For this reason, strain gauges are almost always used in a bridge configuration, with a voltage or current excitation source. The general Wheatstone bridge (Figure 3), consists of four resistive arms with an excitation voltage, V_{EX}, applied across the bridge.

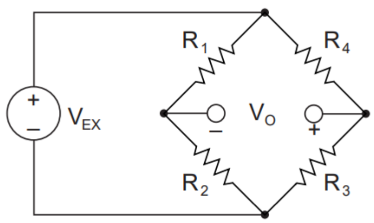

Figure 3. Wheatstone bridge

The output voltage of the bridge, V_O, will be equal to:

$$V_o = \left[\frac{R_3}{R_3+R_4} - \frac{R_2}{R_1+R_2}\right] * V_{EX} \qquad Eq.\ 2$$

By replacing one resistor with an active strain gauge (quarter bridge configuration), any changes in the strain gauge resistance will unbalance the bridge and produce a nonzero output voltage (Figure 4).

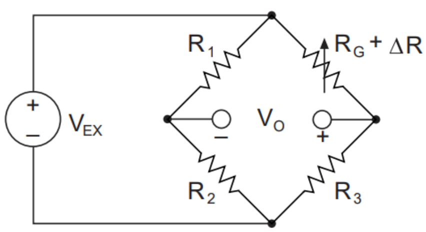

Figure 4. Quarter bridge circuit

The sensitivity of the bridge to strain can be doubled by making two gauges active, but in opposite directions. For example, Figure 5 illustrates a bending beam application with one bridge mounted in tension (R_G + ΔR) and the other mounted in compression (R_G – ΔR).

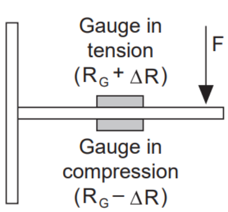

Figure 5. Two strain gauges double the bridge sensitivity

This half-bridge configuration (Figure 6) yields an output voltage that is linear and approximately doubles the output of the quarter-bridge circuit. (Ref. 1 for more detail on bridge configuration options).

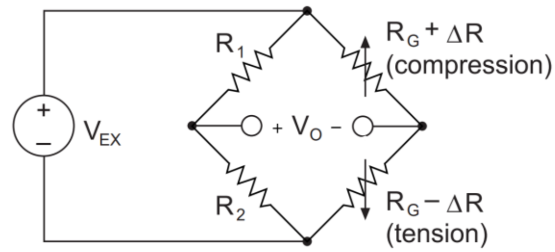

Figure 6. Half bridge circuit

If the nominal resistance of the strain gauge is designated as R_G, then the strain-induced change in resistance, ΔR, can be expressed as

$$\Delta R = R_g * GF * \varepsilon \qquad Eq.\ 3$$

Where identical gauges are used in reverse polarity (each having same R_G and GF) and if R_1 = R_2 = R_G the bridge equation above can be rewritten to express V_O/V_{EX} as a function of strain:

$$\frac{V_O}{V_{EX}} = \frac{GF*\varepsilon}{2} \qquad Eq.\ 4$$

Simulating the Strain Gauge in Spice

The operation of the half bridge structure of Figure 6 may be emulated in Spice using a stepping parameter for the change in strain gauge resistance.

Design Description

1. Excite the bridge including the sensor models using a low impedance voltage reference.
2. Connect the Wheatstone Bridge differential output to high input impedance signal conditioning circuitry used for high gain differential to single ended conversion, low offsets, gain linearity, and high common mode rejection.
3. From the datasheet for the strain gauge being modeled, enter the gauge factor (GF) into SPICE.
4. Enter the nominal strain gauge resistance (R_G) with no applied strain.

Bridge Design Test Considerations

1. Use SPICE parameter stepping (.step param) with a DC Analysis (.op) to sweep from minimum to maximum strain applied to the sensor model.
2. Set the sweep parameter (strain) to the desired usable range of the strain gauge. Strain in the SPICE model is entered as microstrain (i.e., 30000 microstrain = 30000u).
3. Run a SPICE simulation (using the sweep parameter) and confirm that the bridge differential output voltage matches the expected output.

Once the bridge is producing the desired differential output voltage over the intended strain range, connect the bridge with the sensor model to an excitation voltage circuit and signal conditioning circuit to simulate the completed application. Connect the Wheatstone Bridge differential output to high input impedance signal conditioning circuitry used for high gain differential to single ended conversion, low offsets, gain linearity, and high common mode rejection. The accuracy of the bridge readings will be determined by the nominal value and temperature tolerances of the bridge resistors and variations in the value of R_G. A complete bridge circuit is typically calibrated for the effect of temperature and initial offsets.

Design Simulations

This first simulation performs a sweep of strain from 0 to 30000 microstrain using a 4.096V excitation voltage and a strain gauge with a nominal resistance of 120Ω. A table showing sample simulated versus calculated values for output voltage is shown in Table 1. An LTspice (ref. 2) schematic of the sensor model is shown in Figure 7 and a plot of the simulated results is shown in Figure 8. This shows the bridge output to be unipolar from 0V to 0.12288V, as the modeled strain goes from 0 to 30mstrain. Tale 1 shows calculated versus simulated bridge output voltage.

The expected maximum differential bridge voltage, using Eq. 4, with Vex = 4.096 and GF=2, should be a maximum V_{diff} = 4.096V*30mstrain = 0.12288V, as shown in Figure 8 and Table 1.

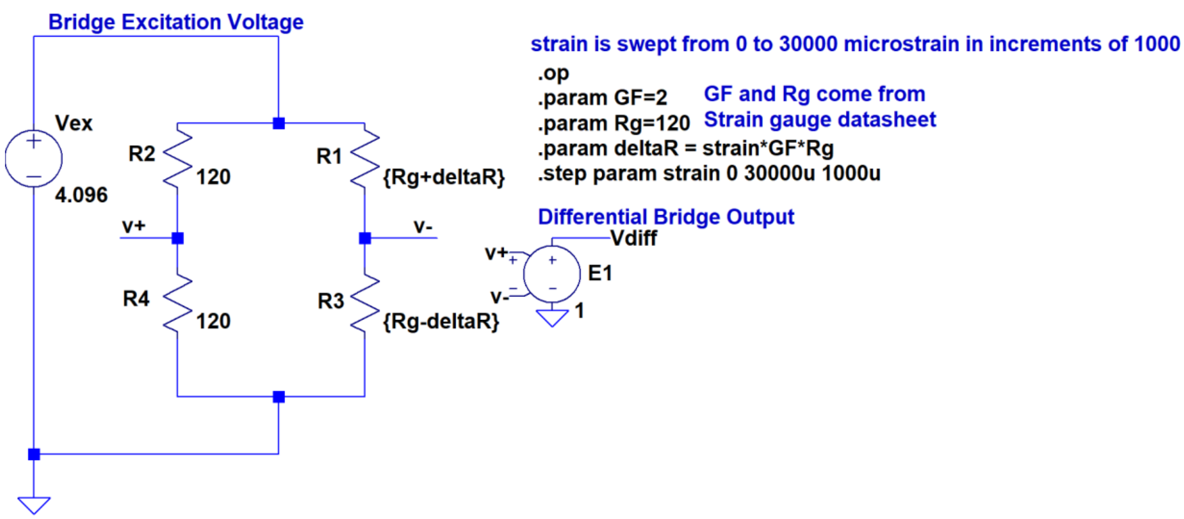

Figure 7. Schematic showing ideal half bridge model and simulation parameters

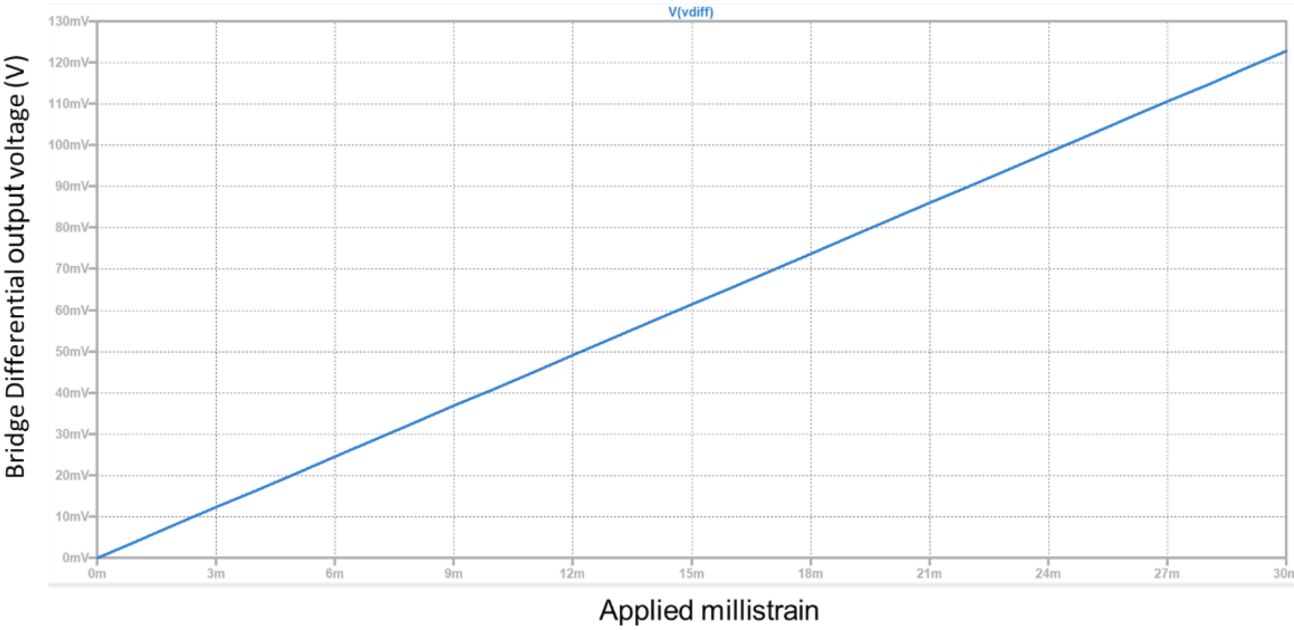

Figure 8. Plot of simulated voltage versus strain (millistrain) using ideal sensor model and 4.096V excitation voltage

Table 1. Simulated versus ideal results

Strain (millistrain)	Calculated Output Voltage (mV)	Simulated Output Voltage (mV)
0	0.00000	0.00000
5000	0.02048	0.02048
10000	0.04096	0.04096
15000	0.06144	0.06144
20000	0.08192	0.08192
25000	0.10240	0.10240
30000	0.12288	0.12288

Design Description

One possible biasing and post-amplifier circuit for the sensor model inside the bridge is shown in Figure 9. This example provides a precision 4.096V voltage bias to the bridge using the LT1461 reference and an output current boost circuit to supply the 4.096V/120Ω = 34.13mA into the sensor bridge. One of the dual AD4528-2 op amps is used in the bias circuit with the 2nd providing a buffer to the REF input to the AD8226 instrumentation amplifier. To operate with best linearity, the single +5V supply biased instrumentation amplifier is set to a 0.2V minimum output using the REF input with a 0V differential input from the sensor bridge. To expand the bridge full scale output of 0.123V to an ADC full scale of 4.0V maximum, we need an instrumentation amplifier gain of (4.0V-0.2V)/0.123V = 30.9V/V. Using the standard value 1.65kΩ shown achieves this using the lower noise and offset AD8226.

The bridge bias circuit uses the PNP 2N3906 to provide the relatively high 34.13mA current into the bridge. It is possible to reduce this bridge current by adding resistors above and/or below the bridge. This will reduce the signal output from the bridge and decrease the SNR – but can save power if that is critical (ref. 3). The 1kohm input and 3.3nF feedback in the bias circuit provide high frequency stability while the 0.1uF capacitor provides noise filtering to the bridge bias voltage. The 10Ω emitter resistor shifts the op amp output pin voltage down 0.34V and provides start up current limiting.

The inputs to the instrumentation amplifier are tapped off at the two bridge midpoints in a polarity to give positive going instrumentation amplifier output voltage and then filtered through a 2.5kHz differential RC filter using the 4kΩ and 10nF elements. C5 and C6 provide common mode noise input filtering. The final RC filter, at the instrumentation amplifier output bandlimits the instrumentation amplifier noise to 10kHz reducing the integrated noise to the ADC input. These low pass filters should be adjusted in the application to the minimum required frequency, to deliver a desired settling time consistent with the ADC update rate and ½ LSB level.

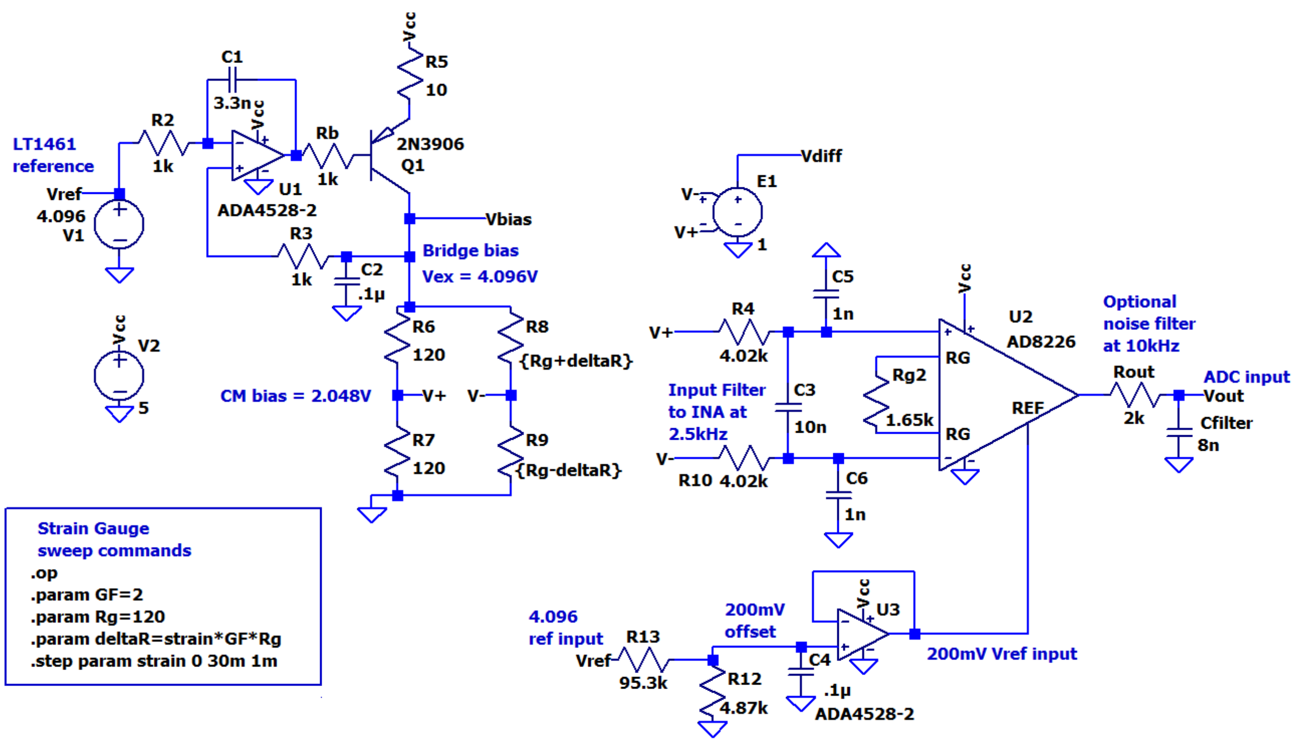

Figure 8. Half bridge application circuit showing excitation and signal conditioning circuit

Design Simulations

Stepping the Strain from 0 to 30mStrain gives the expected 0.2V to 4.0V out of the instrumentation amplifier output to the ADC as shown in Figure 10 and Table 2.

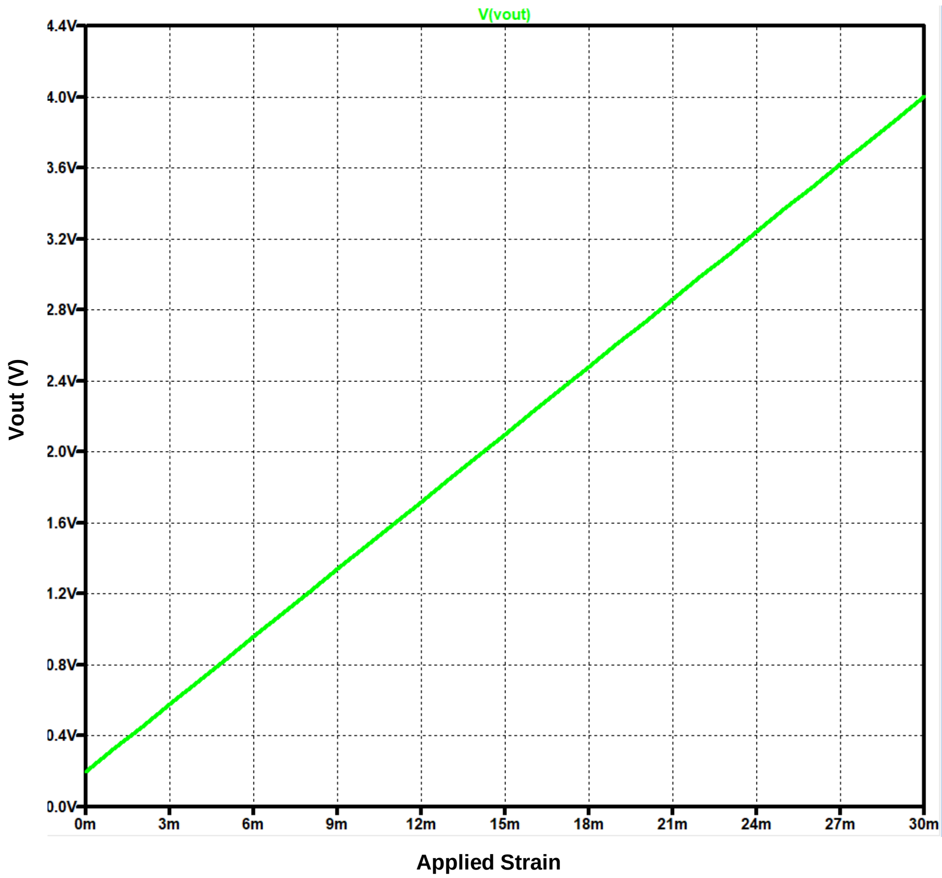

Figure 9. Plot of simulated output voltage versus applied strain in a practical half bridge application circuit of Figure 9

Table 2. Simulated output voltage values for application circuit vs. modelled millistrain

Strain (millistrain)	Vout (V)
0	0.198018
5	0.831897
10	1.464813
15	2.080927
20	2.733645
25	3.367562
30	4.001478

Any reference voltage design as shown in Figure 11 should assess the loop stability. This is done by breaking the loop at the op amp input, injecting a test AC signal, then measuring the gain and phase around the loop back to the op amp differential inputs. An easy simulation trick is to use high L and C values to 1st close the loop (with the large L) to get a DC operating point then open that up on the 1st AC step and use the large C (as it shorts out on the 1st AC step) to inject the test signal as shown in Fig. 11. (ref. 4 – LG simulation techniques using high L&C). Include the ".options gfarad=0" command on the LTspice schematic to ensure there is no DC current in the capacitors when LTspice does a background DC Operating Point analysis, before running the AC Analysis. This ensures a proper linear DC Operating point, which should be confirmed, buy running a separate ".op" analysis first, before the AC analysis.

The key here is to achieve a good DC operating point using the 100Meg inductors, then have the full feedback loop appear as these high L's go high impedance on the first AC step. Since we are injecting the test signal right at the two op amp input pins, the ADA4528 input C terms need to be added separately at the feedback sense points. Those are the two 30pF common mode and 15pF differential input capacitors. The feedback differential signal is sensed, then sent through a dependent source to get single ended loop gain with the correct polarity to show phase margin directly. The bridge stepping is disabled by putting a ";" at the front of that step param line, and instead fixed at 0mStrain is set to leave the bridge simply producing a 0V differential signal and just appearing as a load to the amplifier + 2N3906 loop. Sweeping this LG (Loop Gain) simulation across frequency and looking for the 0dB magnitude crossover frequency shows a very comfortable 50deg phase margin in Figure 12.

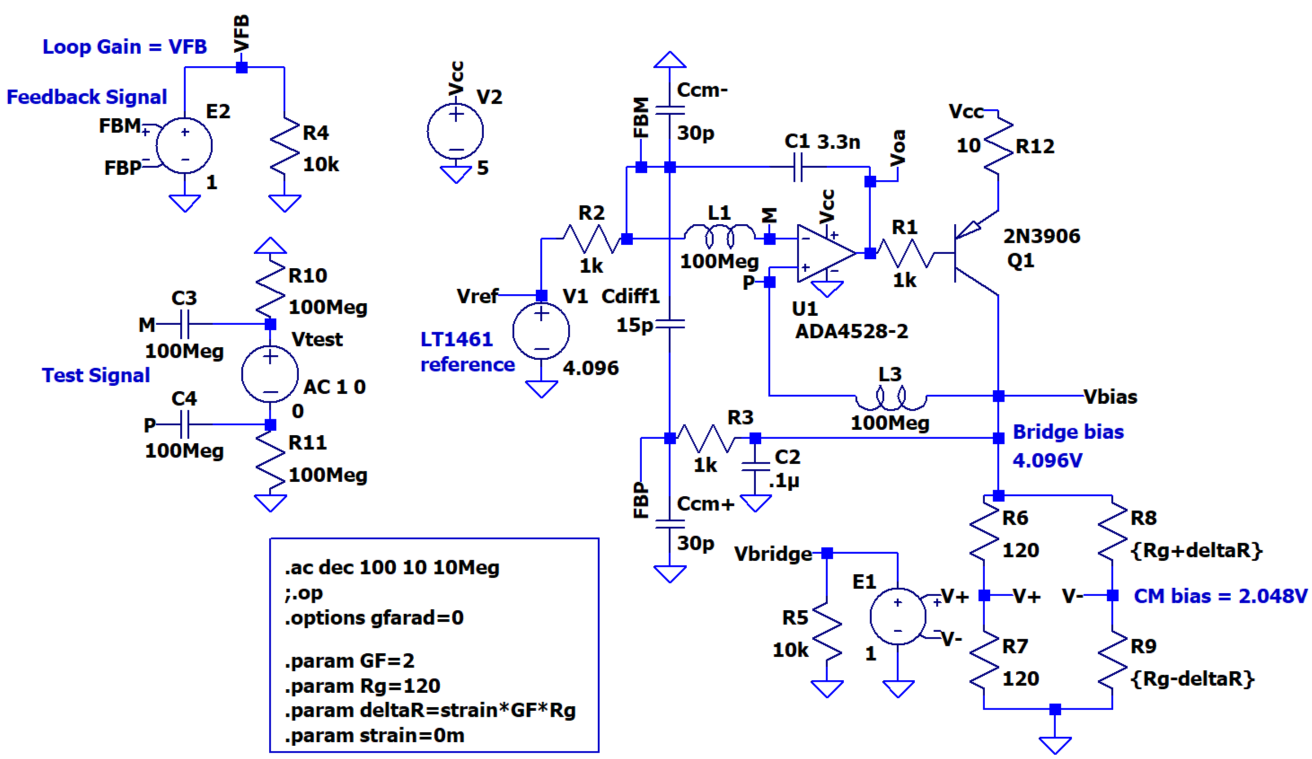

Figure 11. Bridge excitation voltage circuit loop gain analysis for stability

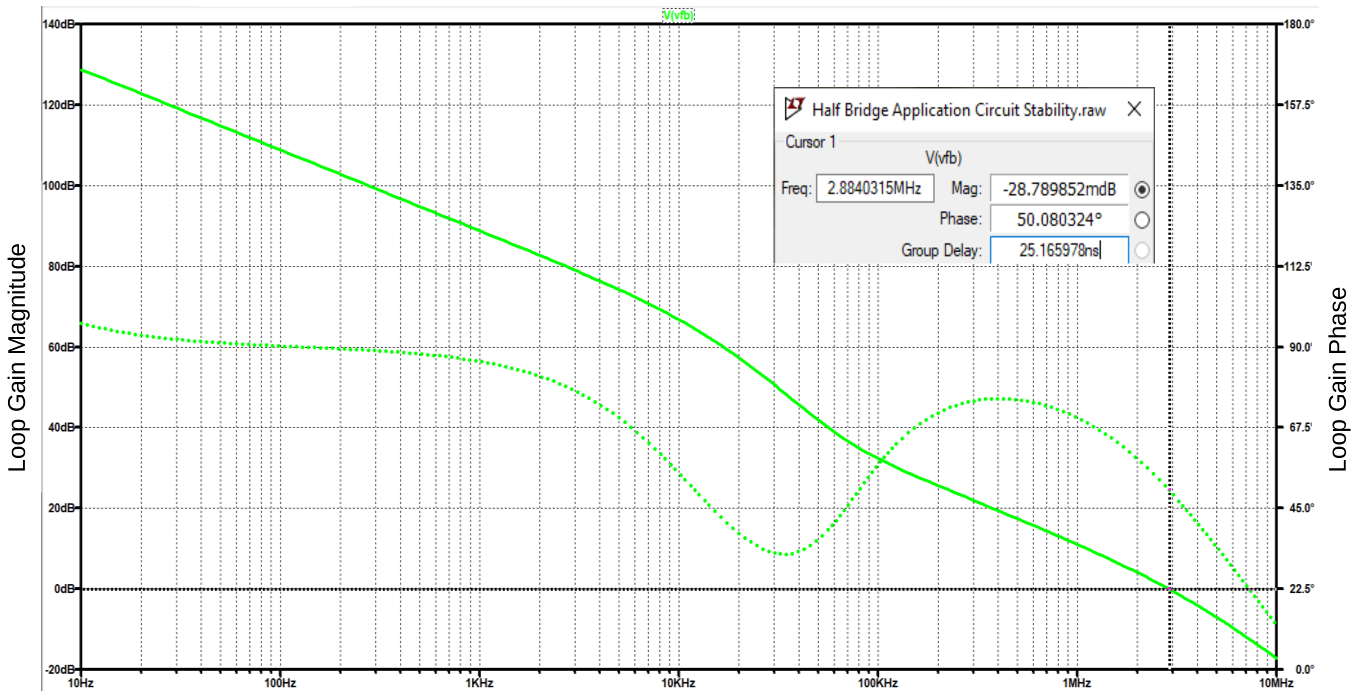

Figure 12. Bridge excitation reference voltage loop gain and phase

In selecting the AD8226 precision instrumentation amplifier, it is very useful to apply the online Analog Devices Instrumentation Amplifier Diamond Tool (ref. 5). This tool allows you to enter the desired external conditions and gain, where it will then screen down to suitable devices and show you internal and external DC voltages, as the differential input signal is swept over the designated range. Figure 13 shows that tool set up for this design and starting with the AD8226 as a candidate device. This device was chosen (over lower power options) as having a much lower input noise voltage and excellent DC precision. Here, the supplies are set to +5V and 0V. The input CM voltage is fixed at 2.048V, the reference voltage is set to 0.2V, to hold the output pin above ground at 0 strain and the differential input sweeps from 0V to 123mV, giving the 0.2V to 4.0V, shown at the output of the Instrumentation Amplifier. Expanding the parameter table for screened devices will show you the parameters for the other Instrumentation Amplifier options for this design.

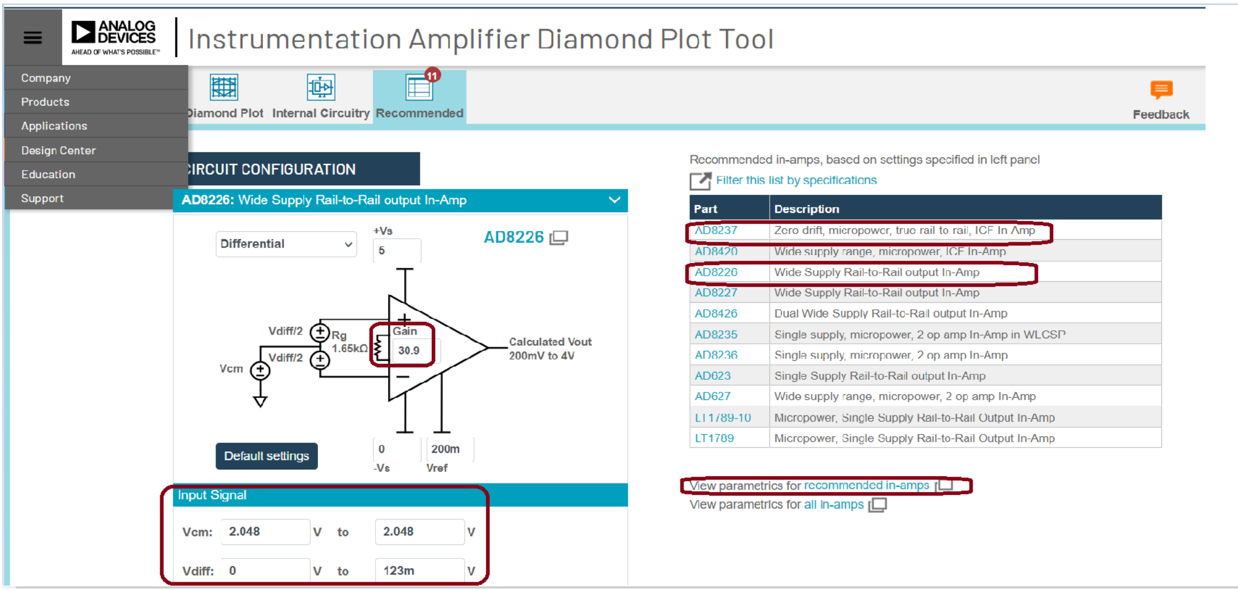

Figure 13. Instrumentation Amplifier Diamond tool set up for this design and showing alternate devices

Design Devices

Table 3. Precision Voltage Reference

Part Number	Vout (typ)	Initial Accuracy (max)	Vout Tempco (max)	Vnoise (typ)	Iout Sourcing (max)	Vs+ (min/max)
LT1461ACS8-4	4.096V	0.04 %	3 ppm/V	32uVpp	50mA	4.4/20 V

Table 4. Instrumentation Amplifier

Part Number	Vos (max)	Ibias(input) (max)	Gain (min/max)	Ios (input) (max)	Vnoise (typ)	CMRR (G=100) (typ)
AD8226	50μV	27nA	1/1000 V/V	1nA	22nV/√Hz	120dB

Table 5. Op Amps (for Bridge Excitation and Instrumentation Amplifier Vref Buffer) (+5V supply specifications)

Part Number	Vos (max)	Ibias (max)	GBP (typ)	Vnoise (typ)	Iq/Amp (typ)	Vs span (min/max)
ADA4528	2.5uV	200pA	6.2MHz	5.6nV/√Hz	1.5mA	2.2/5.5 V

References

"Measuring Strain with Strain Gauges"
White Paper by National Instruments, 2020

LTspice
LTspice® is a high-performance SPICE III simulator, schematic capture and waveform viewer with enhancements and models for easing the simulation of switching regulator, linear, and signal chain circuits.

Modeling a Load Cell in SPICE
"Analog Bits - Modeling a Load Cell in SPICE" Created by Alec Schmidt, last modified on Jun 20, 2017

"Negative Feedback, Part 9: Breaking the Loop"
By Robert Keim, December 8, 2015, "All About Circuits" website.

Instrumentation Amplifier Diamond Plot Tool
The Diamond Plot Tool is a web application that generates a configuration-specific Output Voltage Range vs. Input Common-Mode Voltage graph, also known as the Diamond Plot, for Analog Devices Instrumentation Amplifiers

Acknowledgements

Key Analog Devices Consultant:
Tim Green, Principal Engineer, Product Applications, Precision Amplifiers Group
Michael Steffes, Analog Devices Contract Engineer, Wideband Signal Chains