BYOE: Determining Pressure inside Thin Walled Vessels using Strain Measurements

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ABSTRACT

The objective of this Bring Your Own Experiment session is to demonstrate use of strain gages to measure circumferential strain on a soda can and to infer the internal pressure of the soda can using the stress-strain relationships for thin-walled pressure vessels. Students record transient change of the strain as they open a soda can. As a technical setup, a soda can, a strain gage module, and an Arduino Uno board are used. This experiment is conducted as a part of a junior-level engineering experimentation course in a technological university. Typical student numbers in this course are 30.

In the classroom activity, the students are given the following excerpt:

"You are a product-line engineer for a leading soda company. Recent failures in the product line required you to measure the pressure inside an arbitrary unopened soda can (pressurized). Your team identified a suitable sensor for this purpose: a strain gage mounted on the soda can. Your role will be to set up the experiment so that you can show the change in the soda can's pressure while it is being opened."

In this hands-on lab exercise, students work in teams of two students and prepare their own experimental setups. Students start the experiment by attaching a unilateral strain gage on a soda can (ideally circumferentially or longitudinally). Once the strain gage is fixed on the soda can in an orientation that enables directional strain measurements, students adjust a potentiometer in a Wheatstone bridge to create zero balance. The whole process of establishing a zero-balance bridge is a good learning exercise. Once this balance is achieved, students open the soda can and record the resulting voltage deflection. Next, students calculate the strain using the strain gage constitutive equation with the gage factor of the strain gage, the diameter of the soda can and its wall thickness. The calculated strain is converted to the internal pressure of the soda can, using equations for thin-walled pressure vessels. The students typically find a pressure in the range of 30-60 psig depending upon the brand and type of soda selected.

The deliverables of this experiment are a lab report that contains the following,

- Description of the experimental setup,
- Theoretical background of strain measurements,
- A graph that shows the change in the electric potential as the soda can is opened.
- Calculated strain and pressure from the recorded electric potential as a function of time.
- Final soda can gage pressure,
- Uncertainty analysis based upon the multiple measurements and conclusions.

This experiment is one of most engaging experiments students conduct within the class. Students attach strain gages on soda cans, connect strain gages to a Wheatstone bridge, and conduct a transient experiment to infer pressure. While they are exposed to the theory of strain gages in class, in this lab exercise they have the opportunity to use them. Students initially go through a learning curve setting up their experiments, after which most deliver a report with accurate data. A common mistake in the reports is due to unit conversions when students calculate the interior pressure using the strain data.

DESCRIPTION OF THE EXPERIMENT

This experiment involves measurement of circumferential strain on a soda can to deduce its internal pressure using thin-wall pressure vessel stress-strain relations. The experiment is conducted in mechanical engineering department of a private technological university, and this experiment is a part of a junior-level engineering experimentation course. Students are given the following statement in the beginning of the laboratory experiment,

"You are a product line engineer for a leading soda manufacturing plant. Recent failures in the product line required you to measure the internal pressures of unopened soda cans following their pressurizing and sealing stages. Your team identified a suitable sensor for this purpose: a uniaxial strain-gage that could be mounted on a pressurized can to measure either the longitudinal or circumferential strains. Your role is to set up the experiment to measure the soda can's change in pressure during opening."

In subsequent sections, we describe the theory pertaining to the experiment, hardware used, and results from a single run.

LEARNING OUTCOMES

The learning outcomes of this laboratory exercise are as follows.

- Students are able to apply strain-gages to the pressurized can.
- Students are able to configure an appropriate circuit with sufficient sensor resolution for meaningful results.
- Students are able to perform a conversion between a physical change (strain) and electrical changes, either in resistance or potentials.
- Students are able to apply the stress-strain relationships to determine the pressure change in a thin-walled vessel with statistical confidence.

The objective of this laboratory is to apply the strain gage on a soda can while it is closed and monitor the strain-gage circuit when the can is open. Subsequently, the students consume the soda and then cut the can into strips to determine the can thickness and final pressure determination.

THEORY OF THE EXPERIMENT

This lab uses a strain-gage and a Wheatstone bridge to measure resistance/voltage change during a change in soda-can strain. A schematic for this configuration is given in Figure 1. The deflection voltage of the Wheatstone bridge is the input variable to the data acquisition system. Therefore, the output voltage needs to be related to the change in strain of the soda can. This strain information is then used to determine the internal pressure change based on the physics of thin-walled pressure vessels.

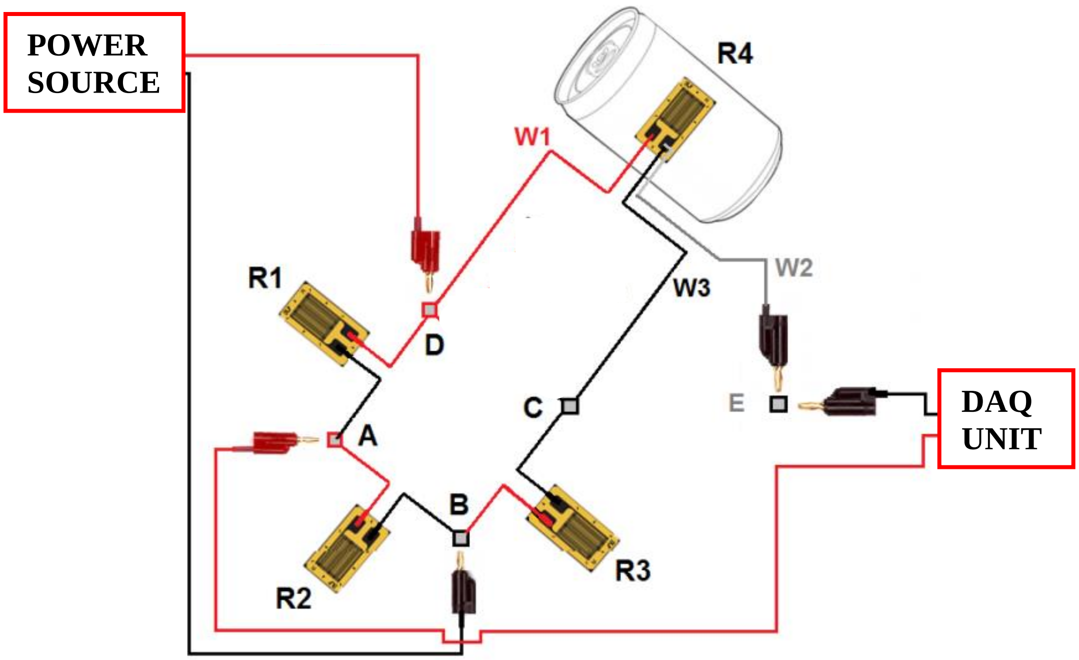

Figure 1. Schematic for the Wheatstone bridge circuit.

Students use a soldering iron to attach a strain-gage on the soda can and electronically wire it as one of the bridge's arm as shown in the schematic in Fig. 1. Students then calculate the pressure inside the soda can relative to the ambient pressure (ΔP) from the Wheatstone bridge deflection voltage as the can's interior pressure released down to atmospheric pressure.

The output of the Wheatstone bridge is the deflection voltage that is proportional to the resistance change in one of the bridge arms when using the bridge in the deflection mode. The equation for the deflection voltage is given to students [1],

$$\delta E_o = E_i \left[\frac{\delta R / R}{4 + \frac{2\delta R}{R}} \right], \tag{1}$$

where E_i is the input voltage to the bridge, δE_o is the bridge deflection voltage as one of the arm's resistance changes by δR from initial resistance of R in a bridge where other arms have equal resistances of R. Once students record the deflection voltage, they use the following relationship to relate the resistance change δR to the strain [1],

$$\varepsilon = \frac{\delta R / R}{GF}. \tag{2}$$

In the above equation, GF stands for the Gage Factor that is specific for the strain gage used. Next, students are given the following equation to relate the pressure change to circumferential strain for a thin-wall pressure vessel [2],

$$\Delta P = \frac{E\ \Delta\varepsilon\ t}{\left[r\left(1-\frac{\vartheta}{2}\right)\right]}, \qquad (3)$$

where, E is the Young's Modulus of the wall material, $\Delta\varepsilon$ is the change in circumferential strain experienced while opening the soda can, t is the wall-thickness of the material, r is the radius of the pressure vessel, and ϑ the Poisson Ratio of this material.

Using equations (1), (2), and (3), students obtain the following relationship between the pressure change and the deflection voltage assuming that the strain on an opened soda can is zero,

$$\Delta P = \frac{E\,\frac{4\frac{\delta E_O}{E_i}}{GF\left(1-2\frac{\delta E_O}{E_i}\right)}t}{\left[r\left(1-\frac{\vartheta}{2}\right)\right]}. \qquad (4)$$

In equation (4), students measure the following quantities to infer the pressure change: δE_o, t, r. Students obtain parameters E and ϑ for the soda can under study using engineering references. The gage factor for the strain gage used is supplied by the vendor on the specifications sheet. In the next section, hardware to measure these quantities are discussed.

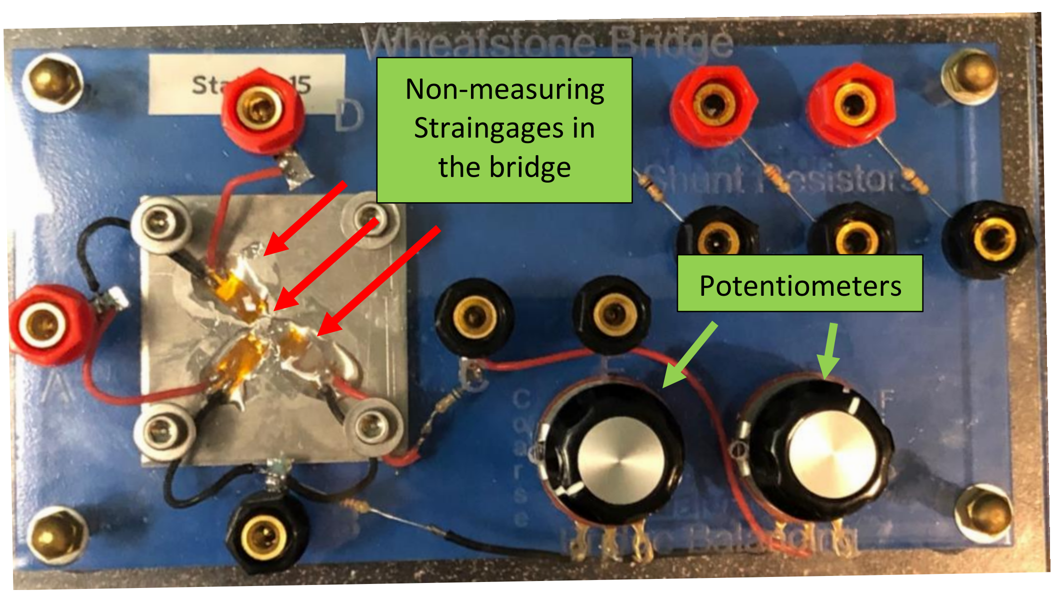

Figure 2. Wheatstone bridge circuit with potentiometers and shunt resistors.

HARDWARE

In the deflection mode, students are first required to balance the bridge so that the deflection voltage is initially at a baseline. This is achieved by adjusting the coarse and fine potentiometers on the in-house built Wheatstone bridge, Fig. 2. The Wheatstone bridge is powered from a 5V voltage source. All four arms in the bridge are composed of strain-gages. While one strain-gage is on the soda can, the strain-gage in the adjacent arm has potentiometers connected in parallel for balancing the bridge. These potentiometers have 240 kΩ and 4.2 kΩ range for coarse and fine adjustment, respectively. Students place the strain-gage circumferentially on the soda can and secure it with an adhesive. The Wheatstone bridge in Fig. 2 uses a three-wire configuration to eliminate the parasitic effects of the lead wires such as the temperature dependence on lead resistance. Once the system is configured, students observe a non-zero deflection voltage. Student adjust the rotary potentiometers with their knobs to balance the bridge. Once the bridge is balanced, students open the soda can and record the deflection voltage. The input voltage to the bridge, E_i is supplied with a cost-effective wall power source. E_i could also be supplied with the Arduino board. The bridge deflection voltage, δE_o are measured with an Arduino Uno Rev 3 that is equipped with a 16-bit Analog to Digital converter. Arduino Uno itself has a 10 bit Analog to Digital Converter; however, the resolution it provides with 3.3V full scale range voltage is not sufficient to resolve the deflection voltage in this experiment. Therefore, students use an extension board that allows 16-bit conversion with adjustable full-scale range voltage. This board is sufficient to resolve the deflection voltage accurately. Students measure the soda can thickness t, and radius, r with a micrometer and Vernier caliper, respectively. Major materials used in the experiment are detailed in Table I. The entire setup to measure strain on the soda can is shown in Figure 3.

Table I. Bill of Major Materials

Part	Description	Manufacturer	Mfg. Part #	Vendor	Vendor Part #	Price	Qty.	Ext
Electronic Prototyping Board	Arduino Uno Rev3	Arduino AG	8058333490090	Arduino AG	8058333490090	$18.70	1	$18.70
Strain gage	Thin foil strain gage	Vishay Precision Group	MMF006836	Micromeasurements	CEA-13-240UZ-120 Educational =	$3.00	1	$3.00
ADC converter	16-Bit ADC - 4 Channel with PGA	Adafruit Industries	1085	Adafruit Industries	1085	$14.95	1	$14.95

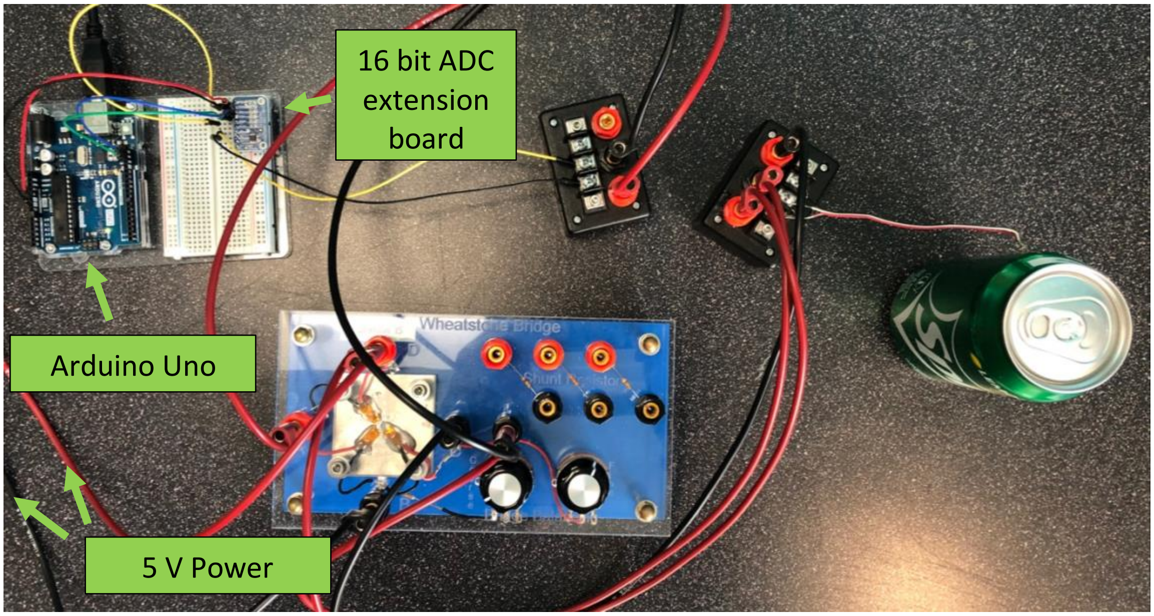

Figure 3. The experimental setup to measure circumferential strain on a soda can.

RESULTS

Figure 4 shows the deflection voltage as a soda can is opened in a representative experiment. The deflection voltage is initially zero (balanced bridge), and as the strain gage goes under compression that is induced by decreased pressure inside the can, the deflection voltage assumes a negative value beginning around data point 36 of Fig. 4. The noise of the Analog to Digital Converter (0.25 mV) is also evident in this graph. The absolute change in the deflection voltage is 3.5 mV. In this representative experiment, equation (4) is used to calculate the pressure change from this voltage change. The pressure change is calculated to be 334 kPa using the following quantities for the soda can, r = 3.32 x 10^{-2} m and t = 1.02 x 10^{-4} m for the soda can studied, E = 69 GPa and ϑ = 0.33 for 3004 grade Aluminum Alloy. This pressure falls into the typical pressure range for soda cans.

Uncertainty Analysis

Next, students perform a simple design stage uncertainty analysis to see the effects of resolution error on the inferred pressure. The uncertainty in the pressure is given by the following equation,

$$u_{\delta E_o} = \frac{\partial \Delta P}{\partial \delta E_o} \cdot E_{\delta E_o} = \frac{4Et}{GF\, r\left(1 - \frac{\vartheta}{2}\right)} \cdot \frac{E_i}{(E_i - 2\delta E_o)^2} \cdot E_{\delta E_o}, \quad (5)$$

where $u_{\delta E_o}$ is for design stage uncertainty and $E_{\delta E_o}$ is for data acquisition resolution error. Using the conversion resolution in our data acquisition system (0.25 mV) and using the parameters reported earlier, the uncertainty is calculated as 23.7 kPa in this representative experiment. Therefore, considering the error due to the bit resolution of the analog to digital converter, the pressure inside the soda can is 334 ±23.7 kPa.

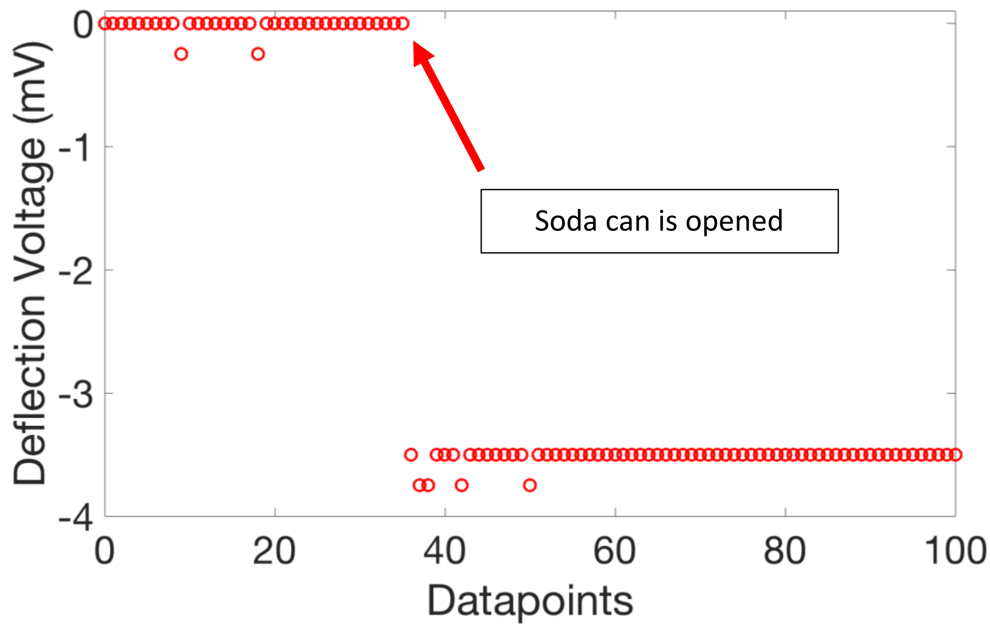

Figure 4. Change of the deflection voltage on the Wheatstone Bridge as a function of pressure change in the soda can.

CONCLUSIONS

Our in-class observations indicate that this project is incredibly interesting to the students. We believe that there are a number of elements that makes this lab exercise interesting to students. First of all, it is a hands-on exercise where students get to see the stress-strain relationship in action. The students enjoy adhering the strain gages on the cans as well as the delicate soldering tasks. The Wheatstone bridge analysis was material they've seen in prior classes, but in this experiment, they actually see it in action. Also, they get to select their choice of soda (and they get to drink them too). As the students determine the pressures in the soda cans and compare with other students, they're amazed that the same soda brands produce similar pressure values and that there are the strong differences in pressures of various brands of soda. A minor problem that students often have with this lab exercise is in the unit conversions as students try to utilize equation (4) to calculate the internal pressure of a soda can. Additionally, some students need to re-do their solder work during the lab as they used too little or too much solder leading to weak connections or short circuits, respectively.

REFERENCES

[1] P. F. Dunn, *Measurement and Data Analysis for Engineering and Science*. 3rd ed. Boca Raton, FL: CRC Press, 2014.

[2] E. P. Popov, *Mechanics of Materials*. New York, NY, Prentice-Hall, 1952