
Wheatstone Bridge Overview

Primary Knowledge Participant Guide

Description and Estimated Time

This Wheatstone Bridge Overview provides information on the electronic circuitry of a Wheatstone Bridge. This overview will help you to understand how a Wheatstone Bridge is used for sensing changes in pressure when used in a micro pressure sensor.

Estimated Time to Complete

Allow approximately 1 hour to complete.

Introduction

A Wheatstone bridge is an electrical circuit design dating back to the early 1800's. It is named for its most famous user, Sir Charles Wheatstone. Sir Wheatstone never claimed to have invented it; however, he did develop multiple uses for it. The Wheatstone bridge circuit was invented by Samuel Hunter Christie (1784-1865) and first described in 1833¹. Sir Wheatstone actually called the circuit a “Differential Resistance Measurer.”

The Wheatstone bridge is one of the most sensitive and precise methods of measuring small changes in resistance. This is possible through its use of transducers (devices which change one form of energy into another, such as mechanical to electrical or electrical to mechanical). The Wheatstone bridge incorporates one or more electrical transducers that change resistance as a result of an environmental change or input (e.g., temperature, pressure, stress). This change is sensed by the circuitry of the Wheatstone bridge which provides a useable electrical output (voltage) representative of the input. The Wheatstone bridge is widely used today in both macro-sized and micro-sized sensors.



Sir Charles Wheatstone²
National Portrait Gallery, London

This unit will describe the basics of the Wheatstone bridge circuit.

Objectives

- Define the variable components of the Wheatstone bridge.
- Describe how the Wheatstone bridge works.

Key Terms (These terms are defined in the glossary at this end of this unit.)

Calibration Curve

Electric circuit

Kirchhoff's Voltage Law

Ohm's Law

Resistance

Resistivity

Resistor

Signal to Noise Ratio

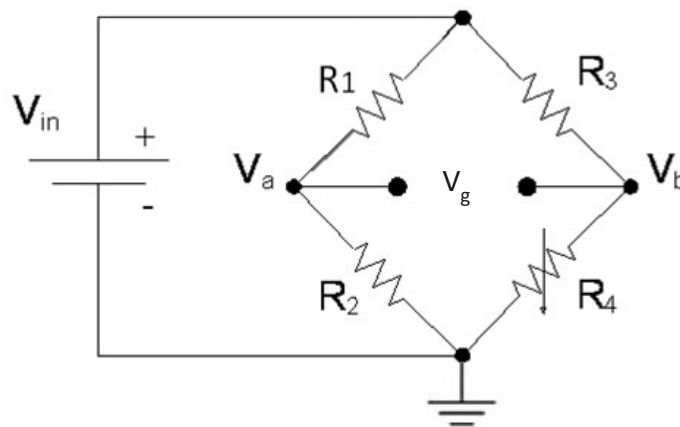
Transducer

Voltage

Wheatstone Bridge

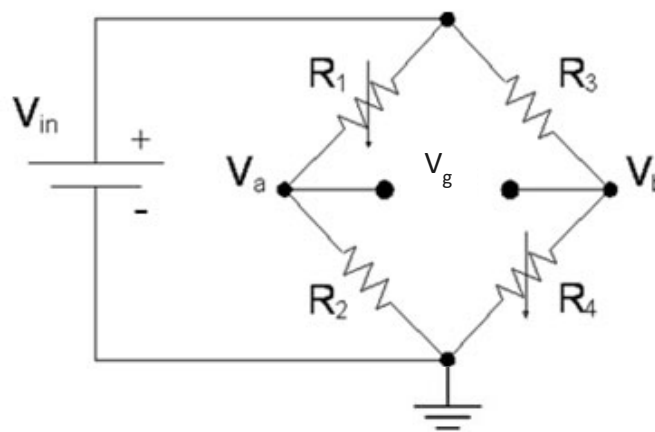
The Wheatstone Bridge

A Wheatstone bridge is a simple circuit used to measure small changes in resistance of a transducer. The classic Wheatstone bridge configuration consists of four resistors, three of which are of fixed value and a fourth which is variable, see R_4 in the diagram below. The variable resistor is the sensing element (transducer). Its design will allow its resistance to change due to a change in an environmental factor such as stress, pressure, or temperature.



Basic Wheatstone Bridge Configuration with one transducer or sensing element (R_4)

Some Wheatstone bridge designs include two variable resistors (sensing elements) to improve the sensitivity of the system, and to provide an enhanced voltage variation as a function of the changing input. When applied to a microsystems pressure sensor system, the bridge circuit has two fixed resistors (R_2 and R_3 below), and two variable resistors (R_1 and R_4) that are the transducers (*see diagram below*). A direct current (DC) voltage source such as a battery provides the input Voltage. The Wheatstone bridge output is called the gap voltage (V_g) and is proportional to the difference in the transducers' resistance values relative to the reference resistance in the bridge configuration. This design allows for the measurement of very small changes in the environmental factor that affects the transducer resistance. The design of the circuit reduces the effects of noise on the output voltage. For example, if the input voltage varies, it does not influence the output voltage since it is related to the ratio of the resistances. Also, a variation in temperature affects all the resistor elements equally and therefore cancel each other out. Therefore, this circuit greatly suppresses electrical noise and thereby improves the signal to noise ratio.



Basic Wheatstone Bridge Configuration with two transducers or sensing elements (R_1 and R_4)

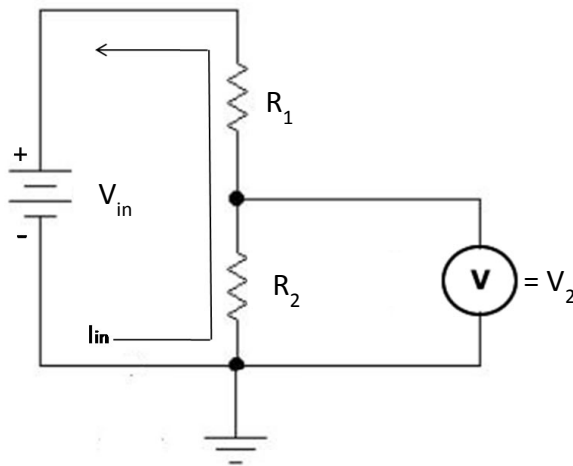
Background Circuits

The Wheatstone bridge is based on a simpler circuit element called the voltage divider. There are two basic concepts needed to understand how these circuit elements operate:

- Ohm's Law ($I=V/R$)
- Kirchhoff's Circuit Laws

Resistor Voltage Dividers

The figure below is made up of two resistors placed in series labeled R_1 , R_2 , and a power supply V_{in} (battery).



Resistive Voltage Divider

The electron flow or current I_{in} is measured in Amperes (A), and travels from the negative terminal of the battery through the resistors to the positive terminal of the battery. As the electrons move through the resistors, they lose some of their energy, and this is measured as voltage drop (reduction) across the resistors.

Ohm's Law

Ohm's Law determines the voltage drop (or change) across a resistor R for a given current I . Ohm's Law states: $V = IR$ where V is the voltage difference across a resistor R that has current I flowing through it. In the Resistive Voltage Divider circuit above, the voltage drop, V_1 across resistor R_1 is written as

$$V_1 = I_{in}R_1$$

and the voltage drop, V_2 across resistor R_2 is

$$V_2 = I_{in}R_2.$$

To measure the V_2 across R_2 with reference to ground, a voltmeter is placed across the resistor. One lead is connected to the node located between R_1 and R_2 , and the other lead is connected to ground (or the negative side of the voltage source). Ground reference voltage is 0 V. The voltmeter reads $V_2 = I_{in}R_2$ and this is the voltage difference which drives current through R_2 .

Note that the current, I , is conserved, in other words, the amount of current flowing into the circuit is the same as the amount flowing out of the circuit. This is analogous to saying that the amount of water flowing into a houses' plumbing circuit is equal to the amount of water flowing out of the same circuit. Water flow is analogous to electrical current flow. However, the water pressure measured coming into the house is higher than the pressure measured going out of the house. The water pressure is analogous to the voltage on a circuit. A thin pipe in a plumbing circuit will allow less water flow (current) and it will also result in a greater pressure drop (voltage change). This thinner pipe is analogous to a resistor having higher resistance.

Let's put some numbers to this Voltage divider circuit and check out our calculations.

$$V_{in} = 10V \quad R_1 = R_2 = 500 \Omega$$

The total circuit resistance R_t is equal to $R_1 + R_2$:

$$R_t = 500 \Omega + 500 \Omega = 1000 \Omega \text{ or } 1 k \Omega$$

Using Ohm's Law, calculate I_{in} .

$$I_{in} = \frac{V_{in}}{R_t} = \frac{10V}{1k\Omega} = 10mA$$

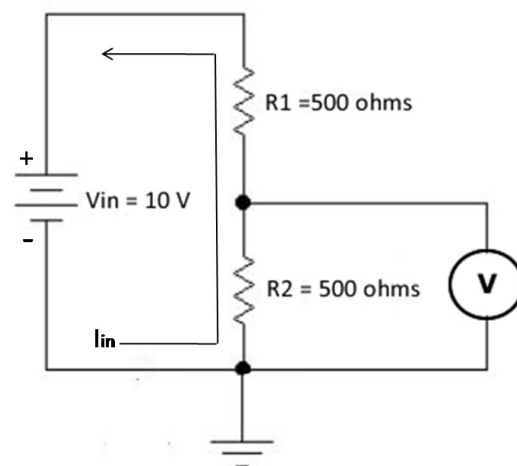
Now you know I_{in} and can determine V_1 .

The voltage drop, V_1 across resistor R_1 is

$$V_1 = I_{in}R_1 \text{ or } 10mA * 500 \Omega = 0.01A * 500 \Omega = 5V$$

The voltage drop, V_2 across resistor R_2 is

$$V_2 = I_{in}R_2 \text{ or } 10mA * 500 \Omega = 0.01A * 500 \Omega = 5V$$



Kirchoff's Laws

Two of Kirchoff's Laws can be applied to find out the voltages and currents in DC circuits.

Kirchoff's current law, states that the sum of all currents entering a node in the circuit is zero.

Another way to look at this is that the current flowing into a node is equal to the current flowing out of it. Kirchoff's voltage law, states that the sum of the voltage drops across a collection of resistors arranged in series (in a line, one after the other) within a circuit is equal to the applied voltage across all the resistors (V_{in}). In this example, it can then be written as

$$V_{in} = I_{in}R_1 + I_{in}R_2 = I_{in}(R_1 + R_2) \text{ or}$$

$$V_{in} = V_1 + V_2$$

Notice in that the previous problem shows this to be true: $10 \text{ v } (V_{in}) = 5 \text{ v } + 5 \text{ v}$

The voltage drop across a specific resistor in series with other resistors is the fraction of that resistor to the sum of the series resistors, multiplied by the applied voltage. (The formula is derived below.)

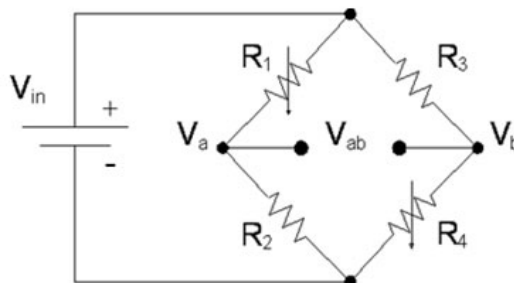
$$I_{in} = \frac{V_{in}}{R_1 + R_2}$$

$$V_2 = I_{in}R_2 = \frac{V_{in}}{R_1 + R_2}R_2 = \frac{R_2}{R_1 + R_2}V_{in}$$

Applying the values of the previous circuit, we get

$$V_2 = \frac{500\Omega}{500\Omega + 500\Omega}10V = 5V$$

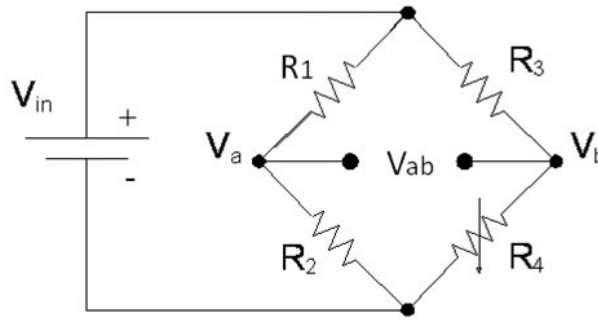
The Wheatstone bridge has two such voltage dividers connected in parallel; therefore, the analysis of the *resistive voltage divider* circuit can be applied to the Wheatstone bridge circuit. Can you identify the two voltage divider circuits in the circuit below?



Wheatstone Bridge with two variable resistors

Wheatstone Bridge and Difference Voltage

One Variable Resistor



Wheatstone Bridge with one variable resistor

The figure above shows the schematic circuit diagram of a Wheatstone bridge. The resistor pair R_1 and R_2 is a *resistive voltage divider* and resistors R_3 and R_4 form another voltage divider in parallel with R_1 and R_2 . The circuit is sensitive to the difference in voltage between node-**a** and node-**b**. V_a and V_b can be found by

$$V_a = \frac{R_2}{R_1 + R_2} V_{in}$$

$$V_b = \frac{R_4}{R_3 + R_4} V_{in}$$

so that

$$V_a - V_b = V_{ab} = \left(\frac{R_2}{R_1 + R_2} - \frac{R_4}{R_3 + R_4} \right) V_{in}$$

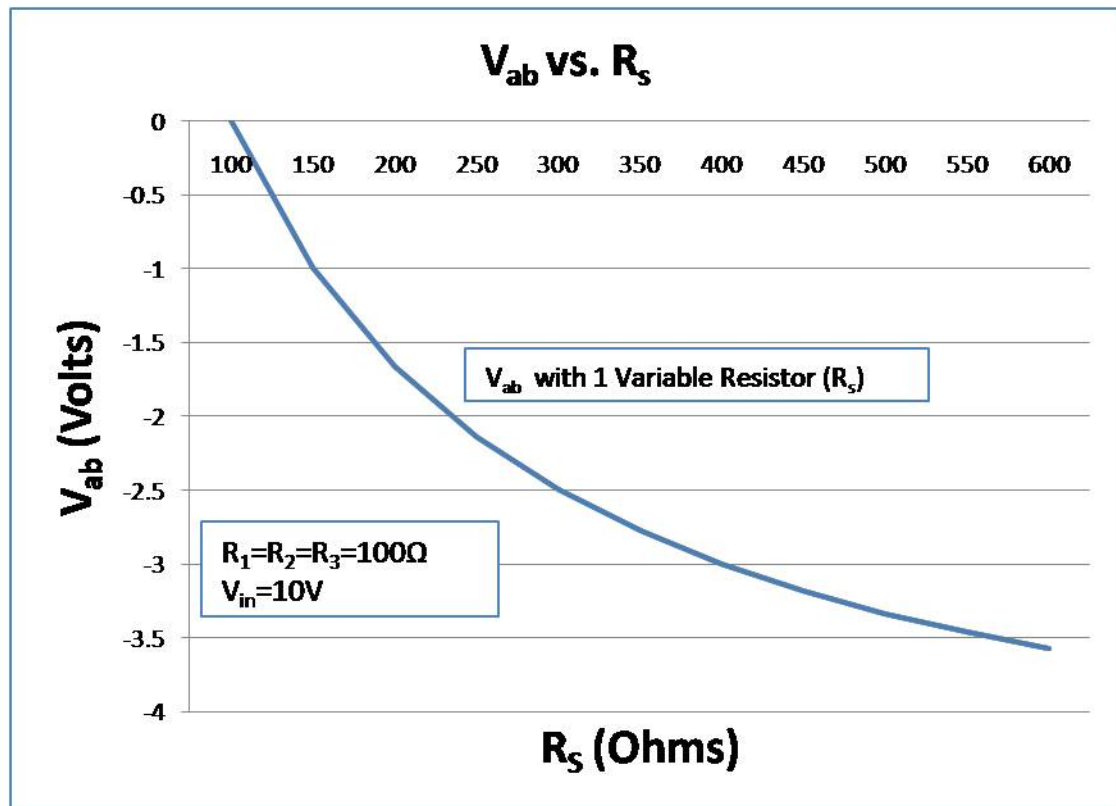
This can also be written as

$$V_{ab} = V_{in} \left\{ \frac{R_2 R_3 - R_1 R_4}{(R_1 + R_2)(R_3 + R_4)} \right\}$$

When $R_2 R_3 = R_1 R_4$, the circuit output is zero, $V_{ab} = 0$. The bridge is said to be balanced when $V_{ab} = 0$ volts. This occurs when $R_1/R_2 = R_3/R_4$. In a typical sensing device, a variable resistor R_4 , is used. The other three resistors are fixed. We will now refer to R_4 as R_S . The Wheatstone Bridge is initially balanced with all of the R 's having the same resistance value by design, including R_S (the resistance of the sensing element when there is nothing to sense). The value of R_S changes when the external environment changes thus affecting V_{ab} as

$$V_{ab} = \left(\frac{R_2}{R_1 + R_2} - \frac{R_S}{R_3 + R_S} \right) V_{in}$$

Assuming the input voltage, $V_{in} = 10V$ and the transducer resistance R_S is initially 100 Ohms (Ω), and $R_1 = R_2 = R_3 = 100 \Omega$, as well, then V_{ab} can be plotted as a function of R_S :

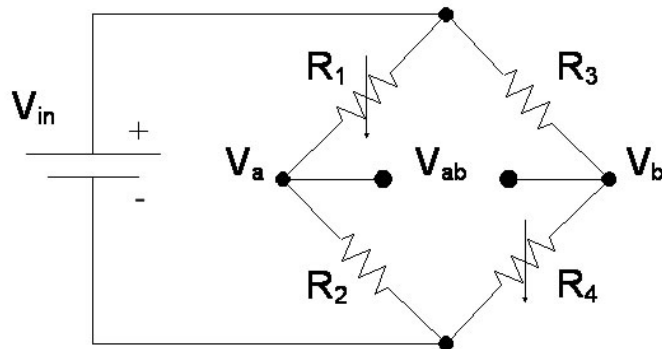


Notice that when $R_S = 100 \Omega$, $V_{ab}=0$ volts and the bridge is balanced. Changes in the environment on the transducer affects its resistance, R_s , creating an unbalanced bridge which results in a voltage related to the resistance change. Based on the graph, if the resistance of R_S increases, V_{ab} decreases.

A similar plot can be made plotting V_{ab} versus the environmental variable associated with the change in resistance.

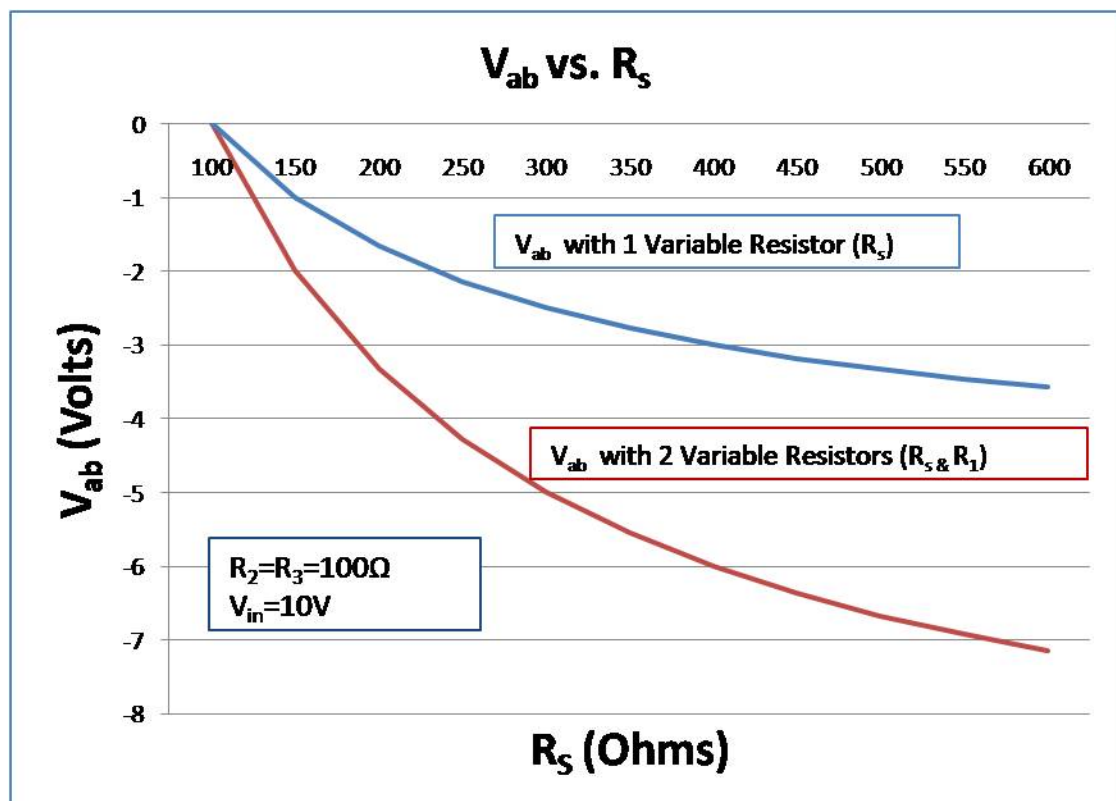
Two Variable Resistors

Looking carefully at the equations and the circuit diagrams, one can design a more sensitive circuit where R_1 and R_4 are both variable resistors. Such a circuit is shown below:

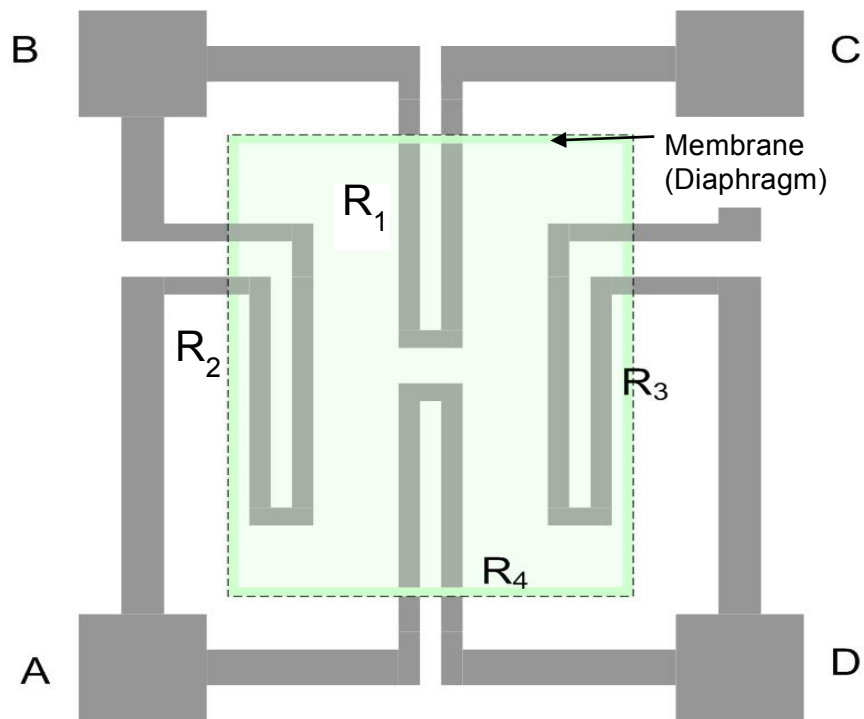


If the R_1 and R_4 resistors are both variable and react in the same manner to an external environmental change, then the effect on the output voltage, V_{ab} is amplified!

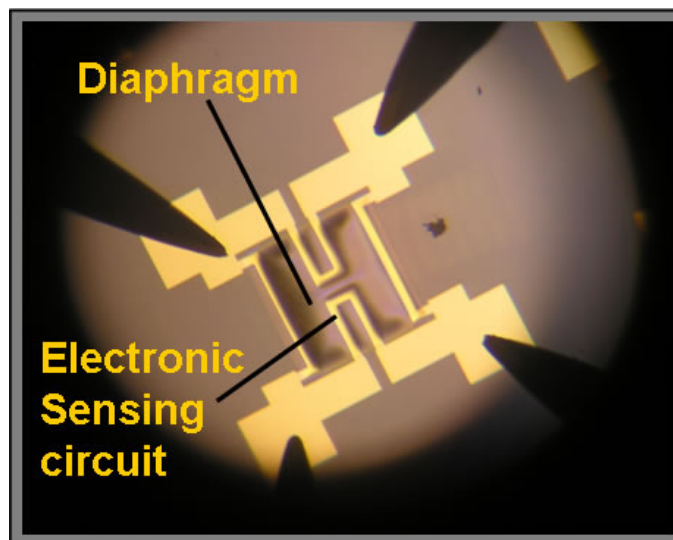
Reconsider the case where all resistances are initially at 100Ω each and V_{in} is 10 V. How would V_{ab} be affected if both R_1 and R_4 both increased to 110 ohms? Graphing V_{ab} as a function of the variable resistances of R_1 and R_4 (in this case changing by the same amount while the other two, R_2 and R_3 remain constant at 100Ω) is shown in the following graph. Note: the variable resistors in the case of a strain gauge pressure sensor will only increase from the nominal value (why would this be?). In the graph below, the blue line represents the case when there is only one variable resistor. The red line represents the transducer response when both R_1 and R_4 are variable.



When the Wheatstone bridge is used in a pressure sensor, the resistors are oriented such that R_1 and R_4 are variable under the stress of a flexible membrane on which they are made.



Wheatstone Bridge layout used in a Pressure Sensor



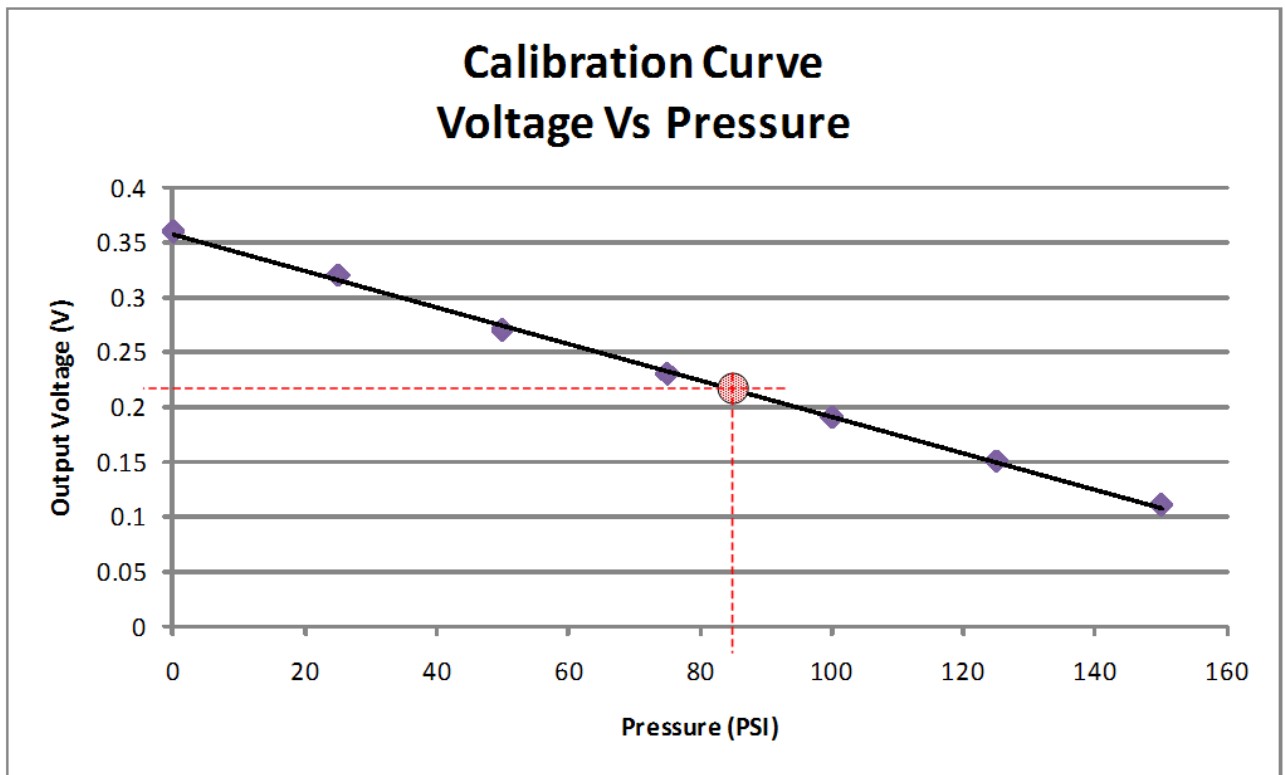
Actual micropressure sensor photo showing the Wheatstone bridge circuit (gold) pattern on top of the silicon nitride membrane. This pattern is slightly different than the schematic.

[Image of a pressure sensor built at the Manufacturing Technology Training Center (MTTC) at the University of New Mexico (UNM)]

Calibration

To calibrate a Wheatstone bridge as a pressure transducer, a series of known pressure differences is applied to the sensing element(s). The output voltage (V_{ab}) is measured using a voltmeter, and V_{ab} versus pressure is plotted. Such a plot is referred to as a calibration curve. When an unknown pressure is subsequently applied and the output voltage read, the calibration curve of V_{ab} vs. Pressure can be used to determine the actual pressure.

The graph below is an example of a calibration curve based on an actual micropressure sensor utilizing a Wheatstone bridge⁵. This graphic shows how to read the curve, for example, if an output voltage of .22 V is read, the corresponding pressure is approximately 82psi.



Summary

A Wheatstone bridge is a simple circuit used to measure transducer responses by measuring changes in voltage. Basic circuit analysis is used to determine the resistance, voltage and current when the bridge is balanced. Any change in transducer resistance causes the bridge output voltage to change corresponding to the change in pressure. A voltmeter measures the output of the Wheatstone bridge and the corresponding pressure is read off of the calibration curve. In a MEMS where the Wheatstone bridge is part of the sensing circuit, its output can be amplified and processed to send information or to initiate a mechanical or electrical response.

References

¹ http://en.wikipedia.org/wiki/Wheatstone_bridge

² <http://www.britannica.com/EBchecked/topic/641626/Sir-Charles-Wheatstone>

³ Dr. Chuck Hawkins, University of New Mexico , Wheatstone Bridge v3.doc

⁵ Hsun-Heng Tsai*, Chi-Chang Hsieh, Cheng-Wen Fan, Young-Chang Chen and Wei-Te Wu
“Design and Characterization of Temperature-Robust Piezoresistive Micro-Pressure Sensor with Double Wheatstone Bridge Bridge Structure”, DTIP of MEMS & MOEMS, 1-3 April, Rome, Italy, 2009.

Glossary of Key Terms

Calibration Curve – A plot of data acquired in the calibration of instrument or device. The curve is used to show how an instrument meets a standard or specification.

Electric circuit – A path or group of interconnected paths capable of carrying electric current.

Kirchhoff’s Voltage Law – The algebraic sum of all voltages in a closed loop of electric circuit must equal zero.

Ohm’s Law - The law stating that the direct current flowing in a conductor is directly proportional to the potential difference between its ends. It is usually formulated as $V = IR$, where V is the potential difference, or voltage, I is the current, and R is the resistance of the conductor.

Resistance – A component’s opposition to current passing through it, resulting in a change of electrical energy into heat or another form of energy.

Resistivity – The measure of how strongly a material opposes the flow of current.

Resistor – An electronic device designed with a specific amount of resistance; used to limit current flow or to provide a voltage drop.

Signal to Noise Ratio (SNR) – The ratio of the amplitude of a desired signal at any point to the amplitude of noise signals at that same point. (i.e., The ratio of a desired signal to the level of background noise.) A ratio less than 1:1 indicates that the background noise is greater than the desired (or reference) noise.

Transducer – A device that converts one form of energy to another form of energy. (e.g., A motor converts electrical energy to mechanical energy.)

Voltage – A representation of the electric potential energy per unit charge. A measurement of the energy contained within an electric field, or an electric circuit, at a given point.

Wheatstone Bridge – A four armed bridge circuit, each arm having a resistor (fixed or variable). It is used to measure an unknown resistance by balancing two arms of the bridge, one of which contains the unknown resistance.

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