Differentiation of the conformance of resistive voltage dividers and Wheatstone bridges to Ohm's law

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Abstract

Sensors are devices that are used to detect and respond to electrical signals. There are multiple factors to consider when designing a resistor, with sensitivity being one of the most important ones. How fast a response changes with regards to a phenomenon determines whether the sensor is sensitive. In this experiment the sensitivity of two kinds of resistive sensors were observed to be able to compare what kind of sensor is better to use. The voltage in the varying resistors for both a voltage divider and Wheatstone bridge were measured and a voltage vs resistance graph was obtained. From the graph obtained, a linear response was observed for both the voltage divider and the Wheatstone bridge, with the Wheatstone having a more linear response and a lower linearity deviation. A possible reason for this is the current that passes through R_1 affects R_t for the voltage divider. High current passing through a resistor causes Joule heating which in turn causes a drift in the measurement of the voltage and as such makes the response in the voltage divider less linear. Overall, the Wheatstone bridge was observed to be a better resistive sensor to use.

Keywords: voltage divider, resistive sensor, Wheatstone bridge, Ohm's law.

1 Introduction

Resistive sensors are commonly used sensors due to their versatility and ease in interfacing with other circuits and computers for data monitoring/processing [1]. Resistive sensors work by measuring voltages, since the resistance cannot be measured directly [2]. Thus, any change in resistance reflects as a change in voltage according to Ohm's law:

$$R = \frac{V}{I} \tag{1}$$

Common physical quantities which can be effectively measured using resistive sensors are temperature, strain, pressure, and light intensity [3]. A major factor that should be taken into consideration when designing a resistive sensor is the desired precision. However, having a precise sensor does not imply that it is an accurate sensor. Small-scale effects, such as ambient temperature, self-heating, electrical noise, and capacitive coupling in breadboards, can introduce a systematic error to the sensor reading which may all be mistaken for noise. In this paper, we explore and compare two types of resistive sensors: a simple voltage divider, and a Wheatstone bridge.

A simple voltage divider (shown in Figure 1) composed of two serial resistors and a voltage source splits a source voltage V_s into values depending on the ratio of the two resistors according to the following relation:

$$V_o = \frac{R_T}{R_1 + R_T} V_s \tag{2}$$

where R_T is also known as the sensing resistor [4]. Such a circuit allows measurement of the resistance of a sensor if interfaced with a microcontroller [5]. It can also be used to scale down a very high voltage so that it can be measured. Plotting a voltage vs resistance curve for this circuit yields a fairly linear curve for low resistance values, indicating that the circuit is ohmic in this regime [6]. However, by moving to a higher resistance regime, the output voltage quickly falls off and the sensor loses sensitivity.

A Wheatstone bridge, on the other hand, takes differential measurements and can provide much higher precision, as opposed to a voltage divider which makes measurements with respect to a common ground [7]. An implementation of this circuit is shown in Figure 2, where it appears like two back-to-back voltage dividers. It is composed of the voltage source V_s, three resistors R_1, R_2, R_3 of known values, the resistor to be measured R_T, and a galvanometer or multimeter $\mathbf{M}$. The objective is to modify the resistance of one of the known resistors until the Wheatstone bridge becomes balanced, such that:

$$\frac{R_T}{R_3} = \frac{R_2}{R_1} = 1 \tag{3}$$

and such that the voltage reading at $\mathbf{M} = 0$ [9]. To achieve this, the resistor at R_2 is usually a potentiometer in order to quickly and conveniently change the resistance value. The voltage at $\mathbf{M}$ can also be calculated as:

$$V_o = V_s \left(\frac{R_T}{R_T + R_3} - \frac{R_2}{R_2 + R_1} \right) \tag{4}$$

If the known resistors have resistances that are known to a high degree of precision, then the resistance of R_T can also be determined with high precision. Consequently, any small change in R_T due to the aforementioned ambient effects, such as temperature change, will disrupt the balance of the bridge, and can easily be detected.

This paper is organized as follows: In Section 2, we illustrate the experimental setup and materials used. In Section 3, we describe and enumerate the parameters considered and methods used in performing the experiment. In Section 4, we analyze and discuss the results. We conclude and summarize the paper and give recommendations to improve similar experiments in Section 5.

2 Experimental Setup and Materials

Figures 1 and 2 show the schematic diagrams of the circuits used in the experiment. The resistor values used for R_T were one each of 100, 120, 150, 180, 220, 270, 330, 380, 470, 560, 680, 820, and three 1000 Ω resistors. A multimeter was used for element $\mathbf{M}$ in the Wheatstone bridge.

3 Parameters and Methodology

The circuits described in Section 2 were constructed on a breadboard. For the voltage divider, the value of R_1 was fixed at 100 Ω, while the value of R_T was switched out after each measurement of V_o with respect to the common ground, for values of $V_s = 2$, 5 and 7 V. For the Wheatstone bridge, the same procedure was followed, but resistors R_1, R_2, R_3 were all kept a constant 1000 Ω, and the voltage across $\bar{bf}$ was measured via direct multimeter connection.

4 Results and Discussion

As expected, the resistor introduced an IR drop proportional to the resistance value as per Ohm's law [8] and this is manifested as the change in the voltage readings. The voltage vs resistance plot of a voltage divider configuration is shown in Figure 3. Experimental results agree with the expected trend of the voltage-resistance (VR) curve (dashed lines represent the characteristic equation as described in Equation 2). In the context of sensors, it is ideal that the VR curve (or the transfer function) behavior is linear, which means that the phenomenon (resistance) and response (voltage) must vary directly with each other [10]. Evidently, the experimental transfer function curve has an over-all great linearity deviation. On lower resistances, there were drastic change in voltage readings as if saturating while on higher resistances, the voltage reading is cut-off as near the initial input voltage. These linearity deviations can be attributed to factors such as the loading effect and Joule heating. Voltmeter devices have an intrinsic resistance to begin with, and connecting it to a set-up with a relatively lower effective resistance caused a drastic change in the reading. This parallel resistance introduced by the measuring device is termed the "loading effect" [10]. Another thing to consider in a voltage divider configuration is that there is a serial connection between R_1 and R_T which means high currents along R_1 will cause higher voltage drops across R_T [4]. Both of these factors explain the steep slope as seen on the transfer function curve for small resistance values. Despite the notable linearity deviation, the simple voltage divider configuration was able to provide an idea as to what one should expect in an ideal sensor device which is a linear response.

In the Wheatstone bridge configuration, the current across R_1 cannot influence R_t since they are now separated into two parallel balanced branches where there is ideally a zero voltage difference (thus, zero current) [9]. Consequently, Joule heating effect manifests but can easily be accounted for. Our experimental results as shown in Figure 4 turned out to have a more linear response with a lower linearity deviation. It is safe to say that the transfer function curve obtained using the Wheatstone bridge has a greater sensitivity since measurements for low resistance values can now be carried out without worrying about voltage saturation. The minimal linearity deviation may be due to the temperature fluctuations which affected the balance of the bridge [4].

5 Conclusions

There are various factors to be considered when using a sensor, and one of the important factors to be considered is its sensitivity, or how it adapts to changes in values. Theoretically, when looking at the graph of the phenomenon and response, a sharper slope and linear slope should be observed, for a system with linear response, as this would mean that the the sensor adapts, even to the minimal changes in the phenomenon. In this experiment, the sensitivity of two different resistive sensors were observed, namely: the voltage divider and Wheatstone bridge. We note that from Ohm's Law, a linear relationship between voltage and resistance is to be expected. From the graphs obtained, both sensors were able to produce transfer functions with linear responses, with the Wheatstone bridge producing a more linear response with low linearity deviation. This may be because current from R_1 does not affect the current in R_t, as compared to the voltage divider wherein it is difficult to control the current passing from R_1 and R_t. For further validation, the current along R_t should also be observed in both sensors, to see whether there is current passing through in a voltage divider, thus contributing to the drift in measurement, and in the Wheatstone bridge to see whether there really is no current for the two parallel branches.

References

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Appendix

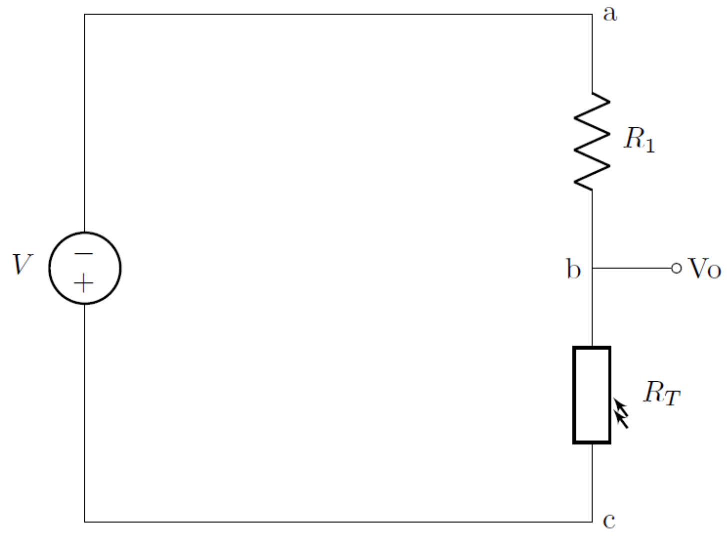

Figure 1: Schematic of a basic voltage divider circuit.

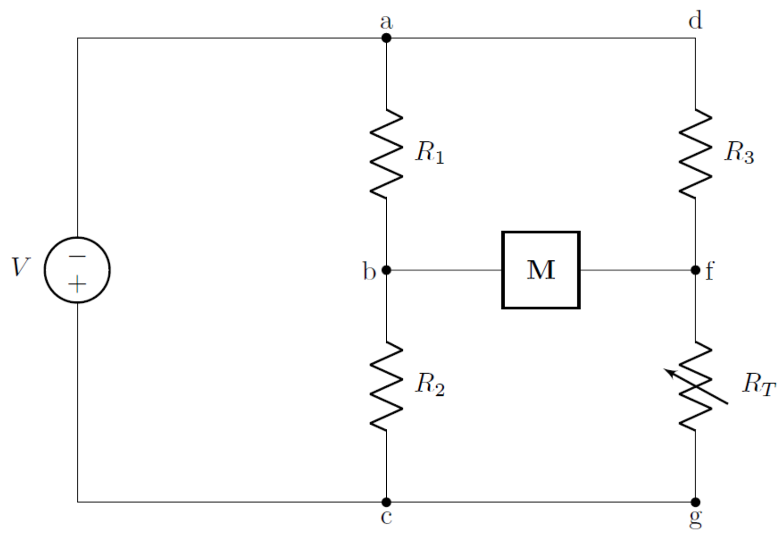

Figure 2: Schematic of a Wheatstone bridge circuit.

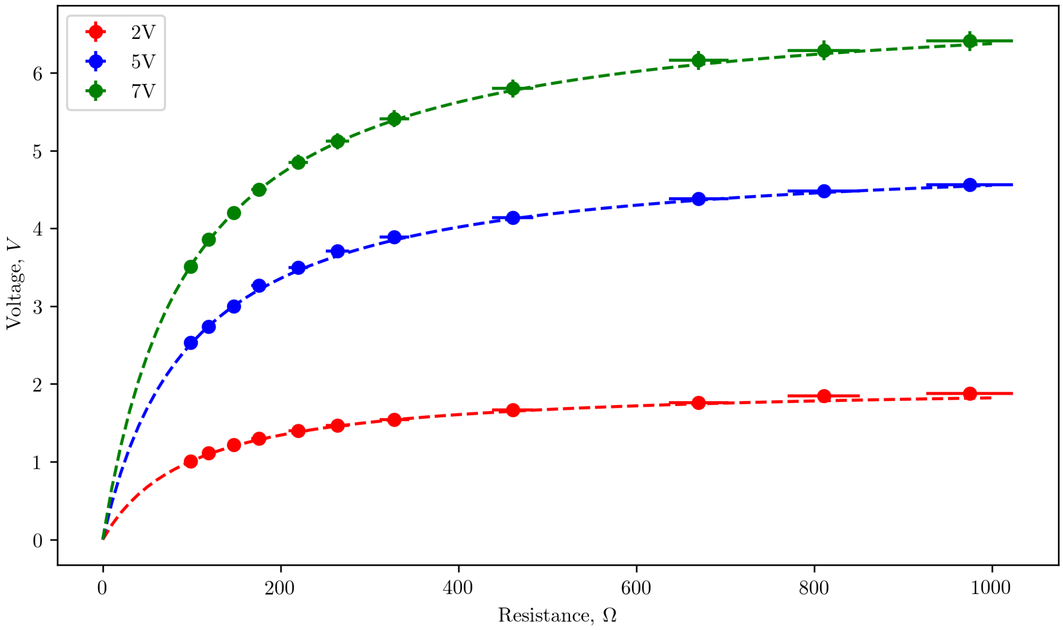

Figure 3: Voltage-resistance curves for a voltage divider.

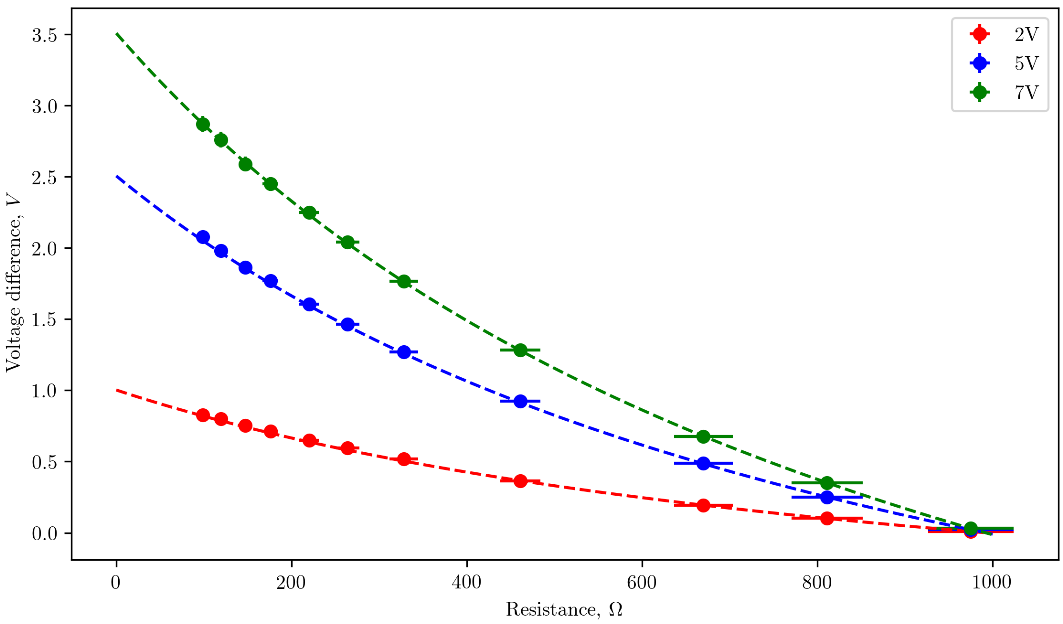

Figure 4: Voltage-resistance curves for a Wheatstone bridge.