3

Chapter Three

Theory

3.1 Load Cell

3.1.1 What is a Load Cell?

A load cell is a sensor or a transducer that converts a load or force acting on it into an electronic signal. This electronic signal can be a voltage change, current change or frequency change depending on the type of load cell and circuitry used. There are many different kinds of load cells. We offer resistive load cells and capacitive load cells. See the figure 3.1

Resistive load cells work on the principle of piezo-resistivity. When a load/force/stress is applied to the sensor, it changes its resistance. This change in resistance leads to a change in output voltage when an input voltage is applied.

Capacitive load cells work on the principle of change of capacitance which is the ability of a system to hold a certain amount of charge when a voltage is applied to it. For common parallel plate capacitors, the capacitance is directly proportional to the amount of overlap of the plates and the dielectric between the plates and inversely proportional to the gap between the plates.

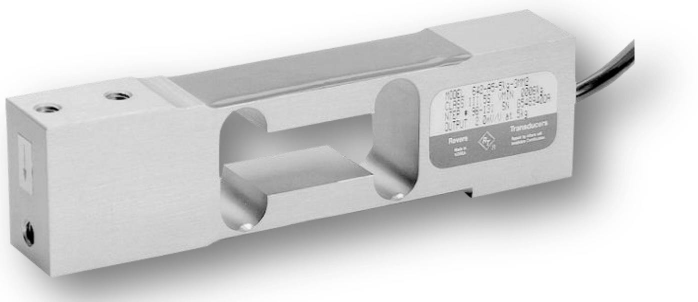

Figure 3.1: Low Profile Aluminum load cell

3.1.2 How do Load Cells Works?

A load cell is made by using an elastic member (with very highly repeatable deflection pattern) to which a number of strain gauges are attached.

In this particular load cell shown in figure 3.2, there are a total of four strain gauges that are bonded to the upper and lower surfaces of the load cell. [7]

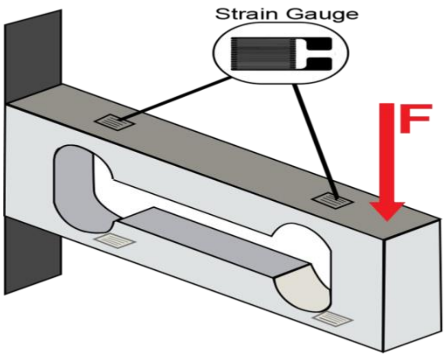

Figure 3.2: Strain Gauges in Load Cell

3.1.3 Strain Gauge

A strain gauge consists of a very fine length of wire that is woven back and forth in a grid and laid on a piece of paper or plastic called its base. A common wire used is a copper nickel alloy with a diameter of about one thousandth of an inch (.001”). The wire is zig-zagged to form a grid so to increase the effective length of the wire that comes under the influence of the force applied to it. Leads are attached to the ends of the gauge. Strain gauges can be made very small, sometimes as small as 1/64”. See the figure 3.3

These gauges are cemented to a strong metal object, commonly referred to as the load receiving element, to make up a load cell. The gauges are configured into a circuit called a *Wheatstone bridge*. [2]

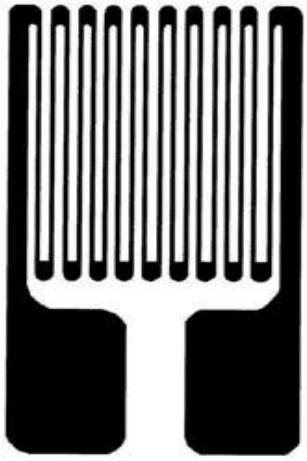

Figure 3.3: Strain Gauge

3.1.4 Wheatstone Bridge Circuit

The four strain gauges are configured in a Wheatstone Bridge configuration with four separate resistors connected as shown in what is called a Wheatstone Bridge Network. An excitation voltage usually 10V is applied to one set of corners and the voltage difference is measured between the other two corners. At equilibrium with no applied load, the voltage output is zero or very close to zero when the four resistors are closely matched in value. That is why it is referred to as a balanced bridge circuit.

When the metallic member to which the strain gauges are attached, is stressed by the application of a force, the resulting strain leads to a change in resistance in one (or more) of the resistors. This change in resistance results in a change in output voltage. This small change in output voltage (usually about 20 mVolt of total change in response to full load) can be measured and digitized after careful amplification of the small mVolt level signals to a higher amplitude 0-5V or 0-10V signal. See the figure 3.4

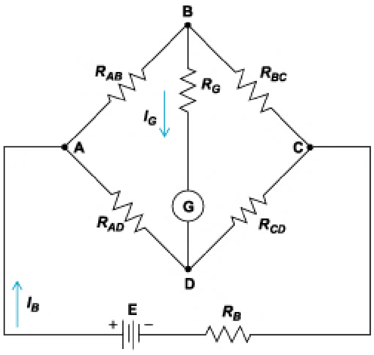

Figure 3.4: Wheatstone Bridge.

3.1.5 Principle of Load Cell

We can take our strain gauge and Wheatstone bridge theories and use them to construct a load cell. We will use a column of steel and glue a strain gauge on each of the four sides of the column. As weight is placed on top of the column, the length of the column would decrease. The column also would become “fatter,” or bulge out. Two strain gauges are placed opposite of each other to respond proportionately to the change in length. [2]

Two other gauges are placed on opposite sides of the column and respond to the change in the column’s bulge. Since one pair of strain gauges become shorter their wire diameters become larger and their resistance decreases. The other pair of strain gauges are positioned so their wires lengthen, thus decreasing their diameter and increasing their resistance. If we hung the same weight from the bottom of the column instead of compressing the column we would be placing tension on it. The column and strain gauges would act in the opposite direction but still stretch and compress the wires by the same amount. See the figure 3.5

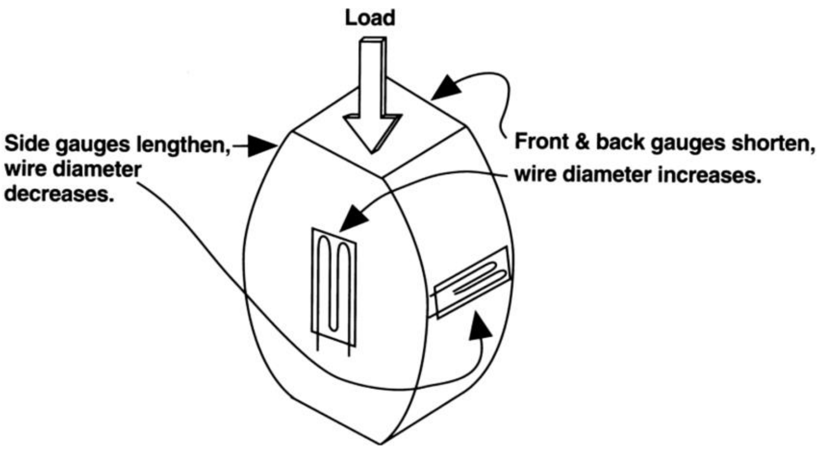

Figure 3.5: Strain Gauge Principle

We can wire our strain gauges into a Wheatstone bridge configuration. We can calibrate the ammeter to read in pounds instead of amps. In effect, we actually have a scale. Of course this is a crude, very inaccurate scale. It is intended to show the basic load cell principle. [2] Load cells are made in different shapes and configurations. The strain gauges are strategically placed for peak performance. See the figure 3.6

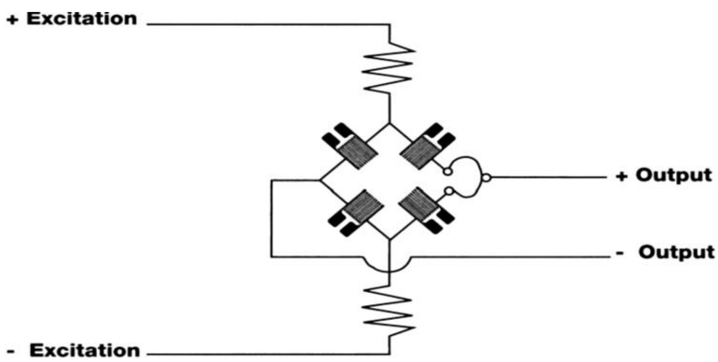

Figure 3.6: load cell principle

The gauge factor GF is defined as:

$$\mathrm{GF} = \frac{\Delta R / R_G}{\epsilon} \qquad \text{………………. Equation (3.1)}$$

Where: ΔR is the change in resistance caused by strain.

R_G is the resistance of the under formed gauge.

∈ is strain.

For metallic foil gauges, the gauge factor is usually a little over 2.For a single active gauge and three dummy resistors in a Wheatstone bridge configuration, the output V from the bridge is: [3]

$$v = \frac{\mathrm{BV.\ GF} . \epsilon}{4} \qquad \text{………………. Equation (3.2)}$$

Where: BV is the bridge excitation voltage.

3.1.6 Load Cell Electrical Theory

The Wheatstone bridge configured above is a simple diagram of a load cell. The resistors marked T1 and T2 represent strain gauges that are placed in tension when load is applied to the cell. The resistors marked C1 and C2 represent strain gauges which are placed in compression when load is applied. [2]

The +In and -In leads are referred to as the +Excitation (+Exc) and -Excitation (-Exc) leads. The power is applied to the load cell from the weight indicator through these leads. The +Out and -Out leads are referred to as the +Signal (+Sig) and -Signal (-Sig) leads. The signal obtained from the load cell is sent to the signal inputs of the weight indicator to be processed and represented as a weight value on the indicator’s digital display.

As weight is applied to the load cell, gauges C1 and C2 compress. The gauge wire becomes shorter and its diameter increases. This decreases the resistances of C1 and C2. Simultaneously, gauges T1 and T2 are stretched. This lengthens and decreased the diameter of T1 and T2, increasing their resistances. These changes in resistances cause more current to flow through C1 and C2 and less current to flow through T1 and T2. Now a potential difference is felt between the outputs or signal leads of the load cell.

Current is supplied by the indicator through the -In lead. Current flows from -In through C1 and through -Out to the indicator. From the indicator current flows through the +Out lead, through C2 and back to the indicator at +In. In order to have a complete circuit we needed to get current from the –In side of the power source (Indicator) to the +In side. You can see we accomplished that. We also needed to pass current through the indicator's signal reading circuitry. We accomplished that as the current passed from the –Out lead through the indicator and back to the load cell through the +Out lead. Because of the high internal impedance (resistance) of the indicator, very little current flows between –Out and +Out.

Since there is a potential difference between the -In and +In leads, there is still current flow from – In through T2 and C2 back to + In, and from -In through C1 and T1 back to +In. The majority of current flow in the circuit is through these parallel paths. Resistors are added in series with the input lines. These resistors compensate the load cell for temperature, correct zero and linearity.

We have replaced the ammeter with a voltmeter which will represent the display on our weight indicator. Also, the leads connected to our indicator are designated +Sig and -Sig. These represent our positive and negative signal leads. The represents our indicator's power supply that provides the precise voltage to excite or power the load cell. The resistance values represent our four strain gauges which make up our load cell.

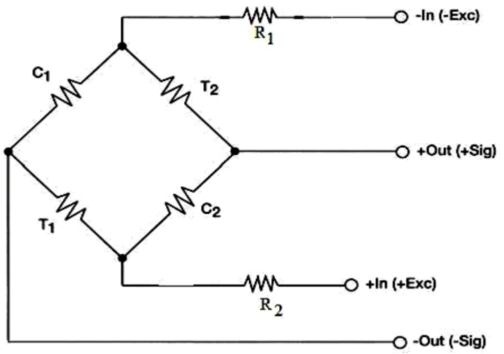

Figure 3.7: Wheatstone bridge

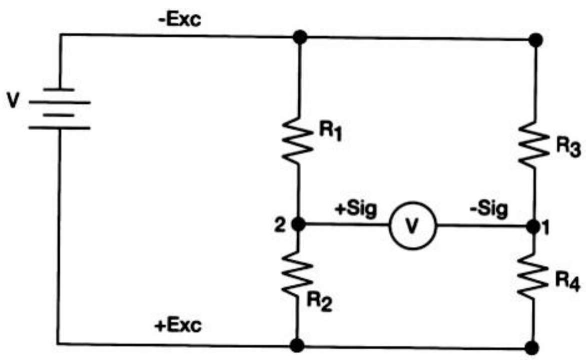

Figure 3.8: Wheatstone bridge with a voltmeter

Now let's place a force on our load cell. Our force caused R1 and R4 to go into tension, which increased their resistances. R2 and R3 went into compression, which decreased their resistances. These changes are depicted in the following diagram.

The current flow in the branch is the branch voltage divided by the branch resistance:

$$I_{R1+R2} = \frac{E_{R1+R2}}{R1+R2} \qquad \text{.................. Equation (3.3)}$$

$$I_{R3+R4} = \frac{E_{R3+R4}}{R3+R4} \qquad \text{………………. Equation (3.4)}$$

From the Figure 3.8 the voltage at point 1 and 2, we can use Ohm's Law.

$$E_{R3} = I_{R3}R_3 \qquad \text{………………. Equation (3.5)}$$

$$E_{R1} = I_{R1}R_1 \qquad \text{………………. Equation (3.6)}$$

3.2 Wiring

A load cell may have a cable with four or six wires. A six-wire load cell, besides having +Ve and -Ve signal and +Ve and -Ve excitation lines, also has +Ve and -Ve sense lines. These sense lines are connected to the sense connections of the indicator.

These lines tell the indicator what the actual voltage is at the load cell. Sometimes there is a voltage drop between the indicator and load cell. The sense lines feed information back to the indicator. The indicator either adjusts its voltage to make up for the loss of voltage, or amplifies the return signal to compensate for the loss of power to the cell.

Load cell wires are color coded to help with proper connections. The load cell calibration data sheet for each load cell contains the color code information for that cell. Rice Lake Weighing Systems also provides a load cell wiring color guide on the back cover of our Load Cell Product Selection Guide. [2]

3.3 Calibration Data

Each load cell is furnished with a calibration data sheet or calibration certificate. This sheet gives you pertinent data about your load cell. The data sheet is matched to the load cell by model number, serial number and capacity. Other information found on a typical calibration data sheet is output expressed in mV/V, excitation voltage, non-linearity, hysteresis, zero balance, input resistance, output resistance, temperature effect on the output and zero balance, insulation resistance and cable length. The wiring color code is also included on the calibration data sheet.

3.4 Output

A load cell's output is not only determined by the weight applied, but also by the strength of the excitation voltage and its rated mV/V full scale output sensitivity.

3.5 Mechanical Theory

3.5.1 Bearing [In this part two cases for chosen the Bearing:]

Case1: No thrust loading just radial loading

1. Compute Fx *and* Fy by applying static equilibrium equations to the shaft supported by the bearing. See the figure 3.9.

2. Find the resultant radial load:

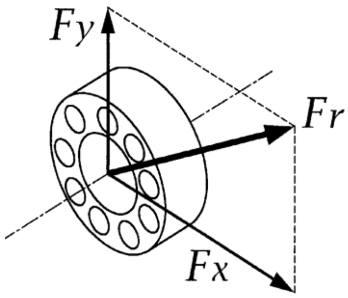

Figure 3.9: Free Body Diagram of Ball Bearing

$$F_r = \sqrt{F_x{}^2 + F_y{}^2} \quad \text{.................. Equation (3.7)}$$

$$F_D = a_f \, V \, F_r \quad \text{.................. Equation (3.8)}$$

Where: F_r is radial load on the bearing.
F_x is the force acting on the x-axis.
F_y is the force acting on the y-axis.
F_D is Design load.
a_f is Application factor we take its value from (Table 4 -1), used because loads are often variable (non-steady) and may increase during operation.
V: rotation factor, takes into account whether the inner or outer race rotates

$$V = \begin{cases} 1.0 \text{ rotating inner ring} \\ 2.0 \text{ rotating outer ring} \end{cases}$$

Usually the inner race of the bearing rotates.

3. Assume the desired life (LD) and Reliability (RD)

$$X_D = \frac{L_D}{L_{10}} = \frac{L_D}{10^6} \quad \text{.................. Equation (3.9)}$$

Where: X_D is Life ratio.
L_D is Design Life.
L_{10} is Rating life and its value equal one million revaluation.

4. Calculate the required catalog rating:

$$C_{10} = \left(\frac{L_D}{L_{10}}\right)^{1/a} * F_D \quad \text{.................. Equation (3.10)}$$

Where: C_{10} is Catalog Rating.

5. Check the catalog and we select a suitable bearing from (Table4-3)

Case2: Radial and thrust loading

1. Compute *Fx* and *Fy* and *Fa* by applying static equilibrium equations to the shaft supported by the bearing.

3. Find the resultant radial load:

$$F_r = \sqrt{F_x{}^2 + F_y{}^2} \quad \text{.................. Equation (3.11)}$$

And calculate the ratio:

$$F_a/V\ F_r \quad \text{.................. Equation (3.12)}$$

4. Assume the desired life (*LD*) and Reliability (*RD*)

$$X_D = \frac{L_D}{L_{10}} = \frac{L_D}{10^6} \quad \text{.................. Equation (3.13)}$$

4. Start with assumed *Fe* (set the initial trial: $F_e = a_f.V.F_r$)

5. Compute C_{10} using:

$$C_{10} = \left(\frac{L_D}{L_{10}}\right)^{1/a} * F_e \quad \text{.................. Equation (3.14)}$$

Factor of Safety:

Is a term describing the capacity of a system beyond the expected loads or actual load. Essentially is how much stronger the system is than it usually needs to be for an intended load.

$$n = \frac{s_y}{t} \quad \text{.................. Equation (3.15)}$$

Where: n is Factor of Safety

s_y is Share stress

t is Material cross section

And we have two type of shear stress:

1) Single shear

$$\tau_{avg} = \frac{P}{A} = \frac{F}{A} \quad \text{.................. Equation (3.16)}$$

2) Double shear

$$\tau_{avg} = \frac{P}{A} = \frac{F}{2A} \quad \text{.................. Equation (3.17)}$$

If the acceleration is known to be constant, the different equation relating time, position, velocity, and acceleration can be integrated.

- $V = V_i + a_c t$ .... Equation (3.18)
- $S_f = S_i + V_i t + \frac{1}{2} a_c t^2$ .... Equation (3.19)
- $V^2 = V_i^2 + 2a_c(S - S_i)$ .... Equation (3.20)

Where: V is velocity
V_i is Initial velocity
a_c is Constant acceleration
t is Time
S_f is Final distance
S_i is Initial distance

If the path of motion is expressed in polar coordinates, the velocity and acceleration component can be related to the time derivative of r and θ

- $V_r = r^{\circ}$ .... Equation (3.21)
- $V_\theta = r\theta^{\circ}$ .... Equation (3.22)
- $a_r = r^{\circ\circ} - r\theta^{\circ 2}$ .... Equation (3.23)
- $a_\theta = r\theta^{\circ\circ} + 2r^{\circ}\theta^{\circ}$ .... Equation (3.24)

Where: V_r is Radial Velocity
r is Position Vevtor
V_θ is Angular Velocity
a_r is Radial Acceleration
a_θ is Angular Acceleration