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WHEATSTONE BRIDGE THEORY AND LOAD CELL APPLICATION

Technical explanation of bridge balance, strain-gage behavior, millivolt-per-volt output, and practical industrial measurement

Subject Area	Industrial instrumentation and sensor signal conditioning	**Sensor Type**	Full Wheatstone bridge strain-gage load cell
Signal Level	Low-level differential bridge output, commonly 1–3 mV/V	**Typical Interface**	Load-cell transmitter, indicator, weigh module, or instrumentation ADC
Practical Use	Force, weight, press load, tension, compression, and process monitoring	**Key Concern**	Accurate excitation, shielding, calibration, and differential measurement

Executive summary

A load cell is not a current-loop device by itself. A bare strain-gage load cell is normally a precision Wheatstone bridge. The bridge is excited with a stable voltage, and the usable signal is a very small differential millivolt output. The output is proportional to bridge excitation and proportional to applied mechanical load after calibration. In most PLC applications, the bridge signal should be handled by a load-cell transmitter, weigh module, or dedicated instrumentation amplifier rather than being connected directly to a standard analog input.

1. Purpose and terminology

The device is correctly called a **Wheatstone bridge**. In load-cell work, the Wheatstone bridge is the electrical circuit that converts very small strain-gage resistance changes into a measurable differential voltage. That voltage is then amplified, filtered, digitized, and scaled into engineering units such as pounds, kilograms, newtons, or press force.

A load cell does not electrically measure "weight" directly. It measures very small elastic deformation of a metal spring element. Bonded strain gages change resistance as that spring element flexes. The Wheatstone bridge converts those resistance changes into a low-level voltage that can be measured accurately.

Practical interpretation: The bridge is the sensor. The load-cell amplifier, transmitter, or weigh module is the measuring instrument. The PLC usually receives a conditioned signal such as 4–20 mA, 0–10 V, Modbus, Ethernet/IP, or scaled digital counts.

2. The basic Wheatstone bridge

A Wheatstone bridge has four resistive arms arranged as two voltage dividers sharing the same excitation supply. The excitation voltage is applied across the top and bottom of the bridge. The signal is measured between the two center nodes.

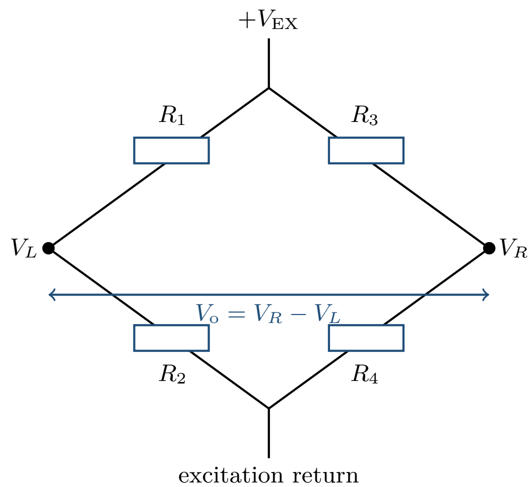

Figure 1: Wheatstone bridge shown as two voltage dividers. The measured output is the difference between the two center nodes.

Using ordinary voltage-divider theory, the left and right bridge node voltages are

$$V_L = V_{EX}\frac{R_2}{R_1 + R_2}, \tag{1}$$

$$V_R = V_{EX}\frac{R_4}{R_3 + R_4}. \tag{2}$$

The differential bridge output is therefore

$$\boxed{V_o = V_{EX}\left(\frac{R_4}{R_3 + R_4} - \frac{R_2}{R_1 + R_2}\right)} \tag{3}$$

This is the exact bridge equation for the node polarity shown in Figure 1. If the instrument defines output as $V_L - V_R$, the sign will reverse, but the magnitude and theory are the same.

3. Bridge balance condition

The bridge is balanced when the two center nodes are at the same voltage. In that condition,

$$V_o = 0. \tag{4}$$

Starting with Equation 3, the balance condition is

$$\frac{R_4}{R_3 + R_4} = \frac{R_2}{R_1 + R_2}, \tag{5}$$

$$R_4(R_1 + R_2) = R_2(R_3 + R_4), \tag{6}$$

$$R_1R_4 + R_2R_4 = R_2R_3 + R_2R_4, \tag{7}$$

$$\boxed{R_1R_4 = R_2R_3}. \tag{8}$$

Equivalent ratio forms are

$$\boxed{\frac{R_1}{R_2} = \frac{R_3}{R_4}} \quad \text{or} \quad \boxed{\frac{R_1}{R_3} = \frac{R_2}{R_4}}. \tag{9}$$

For a load cell, the bridge is trimmed so that with no applied load the bridge is nearly balanced. The no-load signal is usually close to zero, although a real sensor will still have some zero offset.

4. Small resistance changes and bridge sensitivity

In a strain-gage load cell, each bridge resistor is a strain gage or an equivalent bridge element. Under load, each resistance changes slightly. Let each bridge arm be written as

$$R_i = R_0 + \Delta R_i = R_0(1 + \delta_i), \tag{10}$$

where

$$\delta_i = \frac{\Delta R_i}{R_0}. \tag{11}$$

For small resistance changes, the bridge output can be approximated by the first-order linear expression

$$\boxed{\frac{V_\text{o}}{V_\text{EX}} \approx \frac{1}{4}\left(\delta_1 - \delta_2 - \delta_3 + \delta_4\right)} \tag{12}$$

This equation is central to understanding load cells. It shows that bridge output is not controlled by absolute resistance alone. It is controlled by the **pattern of resistance change** across the four arms.

Why the signs matter

In the polarity convention used here, increases in R_1 and R_4 increase output, while increases in R_2 and R_3 decrease output. A properly designed load-cell bridge places tension and compression gages so that their resistance changes add electrically instead of canceling.

5. Strain-gage theory

A metallic strain gage is a resistor whose resistance changes when it is stretched or compressed. The basic strain-gage relationship is

$$\boxed{\frac{\Delta R}{R} = \text{GF}\,\varepsilon} \tag{13}$$

where $\Delta R/R$ is the fractional resistance change, GF is the gage factor, and ε is mechanical strain. For many common metallic foil strain gages, the gage factor is approximately

$$\text{GF} \approx 2. \tag{14}$$

Mechanical strain is dimensionless:

$$\varepsilon = \frac{\Delta L}{L}. \tag{15}$$

Because strain values are small, microstrain is commonly used:

$$1\ \mu\varepsilon = 1 \times 10^{-6}\ \text{strain}. \tag{16}$$

5.1 Example resistance change

Assume 500 $\mu\varepsilon$ and GF = 2. Then

$$\frac{\Delta R}{R} = 2(500 \times 10^{-6}), \tag{17}$$
$$= 1000 \times 10^{-6}, \tag{18}$$
$$= 0.001. \tag{19}$$

That is only a 0.1% resistance change. If the strain gage is 350 Ω, the resistance change is

$$\Delta R = 350\ \Omega(0.001), \tag{20}$$
$$= 0.350\ \Omega. \tag{21}$$

This is why a Wheatstone bridge and precision differential electronics are needed. The resistance change is real, but it is very small.

6. Quarter, half, and full bridge behavior

Bridge sensitivity depends on how many active gages are used and where they are placed in the bridge. Load cells normally use a full bridge because it gives higher signal output and better cancellation of common temperature effects.

6.1 Quarter bridge

In a quarter bridge, only one active gage changes resistance. If R_1 is active and the other arms remain fixed, then

$$\delta_1 = \mathrm{GF}\varepsilon, \qquad \delta_2 = \delta_3 = \delta_4 = 0. \tag{22}$$

Using Equation 12,

$$\boxed{\frac{V_\mathrm{o}}{V_\mathrm{EX}} \approx \frac{\mathrm{GF}\varepsilon}{4}} \tag{23}$$

A quarter bridge can work for experimental strain measurement, but it produces the smallest signal and is the most sensitive to lead-wire and temperature effects.

6.2 Half bridge

In a half bridge, two active gages are used. A common arrangement puts one gage in tension and one in compression so their effects add.

For example,

$$\delta_1 = +\mathrm{GF}\varepsilon, \qquad \delta_2 = -\mathrm{GF}\varepsilon, \qquad \delta_3 = \delta_4 = 0. \tag{24}$$

Then

$$\frac{V_\mathrm{o}}{V_\mathrm{EX}} \approx \frac{1}{4}\left(\mathrm{GF}\varepsilon - (-\mathrm{GF}\varepsilon)\right), \tag{25}$$
$$\boxed{\frac{V_\mathrm{o}}{V_\mathrm{EX}} \approx \frac{\mathrm{GF}\varepsilon}{2}}. \tag{26}$$

This doubles the signal compared with a quarter bridge.

6.3 Full bridge

In a full bridge load cell, all four bridge arms are active. A typical additive arrangement is

$$\delta_1 = +\mathrm{GF}\varepsilon, \qquad \delta_2 = -\mathrm{GF}\varepsilon, \qquad \delta_3 = -\mathrm{GF}\varepsilon, \qquad \delta_4 = +\mathrm{GF}\varepsilon. \tag{27}$$

Substituting into Equation 12,

$$\frac{V_\mathrm{o}}{V_\mathrm{EX}} \approx \frac{1}{4}\left[(+\mathrm{GF}\varepsilon) - (-\mathrm{GF}\varepsilon) - (-\mathrm{GF}\varepsilon) + (+\mathrm{GF}\varepsilon)\right], \tag{28}$$

$$\frac{V_\mathrm{o}}{V_\mathrm{EX}} \approx \frac{1}{4}(4\mathrm{GF}\varepsilon), \tag{29}$$

$$\boxed{\frac{V_\mathrm{o}}{V_\mathrm{EX}} \approx \mathrm{GF}\varepsilon}. \tag{30}$$

A full bridge gives four times the quarter-bridge output for the same strain assumption and provides strong cancellation of common temperature effects.

Bridge Type	Active Gages	Approx. Sensitivity	Practical Comment
Quarter bridge	1	$\mathrm{GF}\varepsilon/4$	Lowest signal; lead-wire and temperature errors require more attention.
Half bridge	2	$\mathrm{GF}\varepsilon/2$	Better signal and compensation when tension/compression gages are paired correctly.
Full bridge	4	$\mathrm{GF}\varepsilon$	Common load-cell arrangement; best sensitivity and common-mode temperature cancellation.

7. How the bridge becomes a load cell

A load cell is a carefully machined spring element with strain gages bonded to locations where strain is predictable and repeatable. The metal body is designed to deflect slightly under load and return elastically when the load is removed.

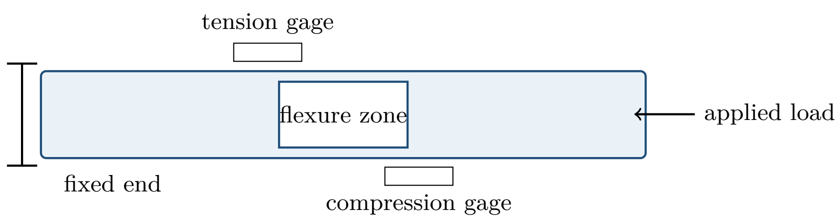

Figure 2: Conceptual load-cell spring element. Actual designs use engineered flexures and gage placement specific to the load direction and capacity.

The measurement process is:

1. Force is applied to the load-cell body.
2. The body deflects by a small amount within its elastic range.
3. Some strain gages stretch and increase resistance.

4. Other strain gages compress and decrease resistance.
5. The Wheatstone bridge converts those resistance changes into a small differential voltage.
6. The measuring electronics amplify, filter, and digitize that voltage.
7. Calibration converts the electrical value into force, pounds, kilograms, newtons, or another engineering unit.

8. Load-cell output rating: mV/V

Most industrial load cells are specified in millivolts per volt, written as mV/V. This is a ratiometric sensitivity rating. It tells how much differential output voltage the bridge produces at full-scale load for each volt of excitation.

A common full-scale sensitivity is

$$S_{\mathrm{FS}} = 2\ \mathrm{mV/V} = 0.002\ \mathrm{V/V}. \tag{31}$$

If the excitation voltage is 10 V, the full-scale bridge output is

$$\begin{aligned} V_{\mathrm{o}}(\mathrm{FS}) &= S_{\mathrm{FS}} V_{\mathrm{EX}}, && (32)\\ &= (0.002)(10\ \mathrm{V}), && (33)\\ &= 0.020\ \mathrm{V}, && (34) \end{aligned}$$

$$\boxed{V_{\mathrm{o}}(\mathrm{FS}) = 20\ \mathrm{mV}}. \tag{35}$$

If the same load cell is excited with 5 V, then

$$\begin{aligned} V_{\mathrm{o}}(\mathrm{FS}) &= (0.002)(5\ \mathrm{V}), && (36)\\ &= 0.010\ \mathrm{V}, && (37) \end{aligned}$$

$$\boxed{V_{\mathrm{o}}(\mathrm{FS}) = 10\ \mathrm{mV}}. \tag{38}$$

The load-cell signal is therefore very small. Even at full load, a bare bridge commonly produces only 10 to 30 mV before amplification.

9. Scaling bridge output to load

For an ideal linear load cell,

$$\frac{V_{\mathrm{o}}}{V_{\mathrm{EX}}} = S_{\mathrm{FS}} \frac{F}{F_{\mathrm{FS}}}, \tag{39}$$

where F is the applied force or load, F_{FS} is the full-scale capacity, and S_{FS} is the rated full-scale sensitivity in V/V.

Solving for load,

$$\boxed{F = F_{\mathrm{FS}} \frac{V_{\mathrm{o}}/V_{\mathrm{EX}}}{S_{\mathrm{FS}}}} \tag{40}$$

9.1 Example calculation

Assume:

$$\begin{aligned} F_{\mathrm{FS}} &= 1000\ \mathrm{lb},\\ S_{\mathrm{FS}} &= 2\ \mathrm{mV/V} = 0.002\ \mathrm{V/V},\\ V_{\mathrm{EX}} &= 10\ \mathrm{V},\\ V_{\mathrm{o}} &= 8\ \mathrm{mV} = 0.008\ \mathrm{V}. \end{aligned}$$

The measured output ratio is

$$\frac{V_\mathrm{o}}{V_\mathrm{EX}} = \frac{0.008}{10}, \tag{41}$$

$$= 0.0008 \text{ V/V}. \tag{42}$$

Then the load is

$$F = 1000\frac{0.0008}{0.002}, \tag{43}$$

$$= 400 \text{ lb}. \tag{44}$$

Practical rule

For load-cell calculations, it is often cleaner to work in V/V or mV/V instead of raw voltage. This is why precision weigh systems often use ratiometric ADC measurement.

10. Instrumentation amplifier and common-mode voltage

The two bridge output nodes are not usually near ground. In a balanced bridge with single-ended excitation, both signal nodes are approximately halfway between excitation and return:

$$V_L \approx V_R \approx \frac{V_\mathrm{EX}}{2}. \tag{45}$$

The useful signal is the small difference between them:

$$V_\mathrm{o} = V_R - V_L. \tag{46}$$

For a 10 V excitation system, each signal lead may sit near 5 V, while the useful full-scale differential signal may only be 20 mV. This requires a differential amplifier or instrumentation amplifier with high common-mode rejection.

A simplified amplifier relationship is

$$V_\mathrm{amp} = GV_\mathrm{o} + V_\mathrm{offset}, \tag{47}$$

where G is amplifier gain.

If a 20 mV full-scale bridge signal must be expanded to a 5 V ADC range, the approximate gain is

$$G = \frac{5 \text{ V}}{20 \text{ mV}}, \tag{48}$$

$$= \frac{5}{0.020}, \tag{49}$$

$$\boxed{G = 250}. \tag{50}$$

11. Four-wire and six-wire load-cell connections

A common four-wire load cell has excitation and signal pairs. A six-wire load cell adds sense leads so the instrument can measure actual excitation at the load cell rather than only at the instrument terminals.

Terminal	Common Marking	Purpose
Positive excitation	EXC+, E+, $+V_{\mathrm{EX}}$	Supplies bridge power.
Negative excitation	EXC-, E-, $-V_{\mathrm{EX}}$ or return	Bridge excitation return.
Positive signal	SIG+, S+, OUT+	Positive side of the differential bridge output.
Negative signal	SIG-, S-, OUT-	Negative side of the differential bridge output.
Positive sense	SEN+, Sense+	Six-wire only; measures actual positive excitation at the load cell.
Negative sense	SEN-, Sense-	Six-wire only; measures actual excitation return at the load cell.
Shield	Shield, drain, screen	Cable shield; normally not a signal conductor.

Sense wires are useful on long cable runs because excitation lead resistance causes voltage drop. If the indicator or transmitter supports sense feedback, it can compensate for that voltage drop.

12. Ratiometric measurement

A ratiometric measurement compares bridge output to bridge excitation. This is valuable because bridge output is proportional to excitation voltage:

$$V_{\mathrm{o}} \propto V_{\mathrm{EX}}. \tag{51}$$

If excitation drifts upward by 1%, the raw bridge output also drifts upward by approximately 1% for the same load. However, the ratio remains approximately constant:

$$\frac{V_{\mathrm{o}}}{V_{\mathrm{EX}}} \approx \text{constant for the same load.} \tag{52}$$

This is why many load-cell ADCs use the excitation voltage, or a divided version of it, as the ADC reference. The measurement then follows the bridge ratio instead of depending only on an assumed fixed excitation voltage.

13. Zero balance, tare, and calibration

A real load cell rarely produces exactly zero output with no load. Small offsets come from gage mismatch, bonding strain, mechanical preload, electronics offset, and temperature.

A practical linear calibration model is

$$y = mx + b, \tag{53}$$

where x is the measured electrical value and y is the engineering value.

Using two known calibration points,

$$(x_1, y_1) = \text{first calibration point,} \tag{54}$$

$$(x_2, y_2) = \text{second calibration point,} \tag{55}$$

the slope and offset are

$$\boxed{m = \frac{y_2 - y_1}{x_2 - x_1}} \tag{56}$$

and

$$\boxed{b = y_1 - m x_1}. \tag{57}$$

Then any later measurement is converted by

$$\boxed{y = mx + b}. \tag{58}$$

13.1 Tare

Tare is a zeroing operation. It records the current unloaded or container-loaded reading and subtracts it from later readings. If x_{tare} is the tare reading, then

$$x_{\text{net}} = x_{\text{measured}} - x_{\text{tare}}. \tag{59}$$

The net reading is then scaled into load using the calibration factor.

14. Temperature compensation

Temperature changes affect strain-gage resistance. A full bridge helps cancel this because all four gages tend to experience similar temperature-driven resistance changes.

If every arm changes by the same fractional amount,

$$\delta_1 = \delta_2 = \delta_3 = \delta_4 = \delta_T, \tag{60}$$

then Equation 12 gives

$$\frac{V_o}{V_{\text{EX}}} \approx \frac{1}{4}(\delta_T - \delta_T - \delta_T + \delta_T), \tag{61}$$

$$= 0. \tag{62}$$

This is the main reason a full bridge is preferred in precision load cells: common changes cancel, while strain-induced opposite changes add.

Temperature compensation is not perfect because real materials, adhesives, lead wires, and electronics are not ideal. However, bridge symmetry makes the system far better than a single-resistor measurement.

15. Important real-world error terms

Term	Meaning
Zero offset	Output present at no load. Removed or reduced by tare/zero calibration.
Span error	Difference between actual sensitivity and rated sensitivity. Corrected by calibration.
Nonlinearity	Output is not perfectly proportional to load across the full range.
Hysteresis	Output differs depending on whether load is increasing or decreasing.
Creep	Output slowly changes under a constant load.
Repeatability	Ability to return to the same output for repeated same-load conditions.
Temperature drift	Zero or span changes caused by temperature.
Electrical noise	Unwanted signal pickup from motors, VFDs, contactors, grounding, or long cables.

16. Practical industrial wiring guidance

Because the bridge signal is small, wiring practices matter.

- Use shielded cable for load-cell wiring.
- Keep signal wiring away from VFD output leads, motor leads, contactors, solenoids, and high-current conductors.
- Treat SIG+ and SIG- as a differential pair.
- Do not use the shield as a signal conductor.
- Avoid grounding the shield at multiple points unless the instrument manual specifically requires it.
- Use the manufacturer's wire color code for the exact load cell. Color codes are common but not universal.
- For long cable runs, use six-wire sense connections when the indicator or transmitter supports them.
- For PLC use, convert the bridge signal with a load-cell transmitter or weigh module before feeding a standard analog input.

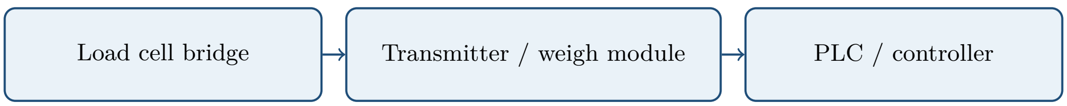

Figure 3: Preferred industrial arrangement for PLC use: mV/V bridge signal into a transmitter or weigh module, then 4–20 mA, 0–10 V, or digital data to the PLC/controller.

17. Core equations at a glance

Most important equations

$$V_o = V_{EX}\left(\frac{R_4}{R_3+R_4} - \frac{R_2}{R_1+R_2}\right) \tag{63}$$

$$R_1R_4 = R_2R_3 \qquad \text{balanced bridge} \tag{64}$$

$$\frac{V_o}{V_{EX}} \approx \frac{1}{4}\left(\delta_1 - \delta_2 - \delta_3 + \delta_4\right) \tag{65}$$

$$\frac{\Delta R}{R} = \mathrm{GF}\varepsilon \tag{66}$$

$$F = F_{FS}\frac{V_o/V_{EX}}{S_{FS}} \tag{67}$$

18. Summary

The Wheatstone bridge is useful in load cells because it converts very small resistance changes into a measurable differential voltage. In a full bridge, gages are placed so that tension and compression resistance changes add electrically. The resulting output is normally rated in mV/V, meaning the signal is proportional to excitation voltage and full-scale load.

For troubleshooting, remember that a load-cell signal is normally a very small differential voltage riding on a much larger common-mode voltage. The measuring instrument must provide stable excitation, high common-mode rejection, proper filtering, and accurate calibration. For most machine-control applications, the safest and most reliable arrangement is a load-cell transmitter or PLC weigh module between the bridge and the controller.