Vehicle Scales

Digital Compensation
in POWERCELL Load Cells

Background

Certain weighing errors are inherent to all strain gage load cells. The factors that cause these errors are both internal (design, material properties, and manufacturing techniques) and external (temperature, time, and load). Figure 1 illustrates some typical load cell metrology errors and how they vary from ideal performance.

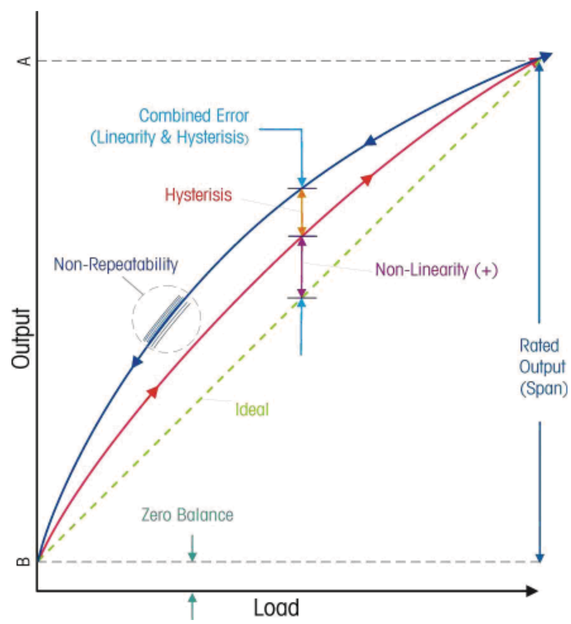

Figure 1: Uncompensated Calibration Curve

The key to increasing a load cell's weighing accuracy is reducing the effect of internal and external influence factors. Achieving higher accuracy requires "tuning" each load cell through a process known as compensation.

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The objective of compensation is to obtain a perfectly linear relationship between the load cell's output and the applied load regardless of temperature or time of loading. Figure 2 illustrates the output of a perfectly compensated load cell.

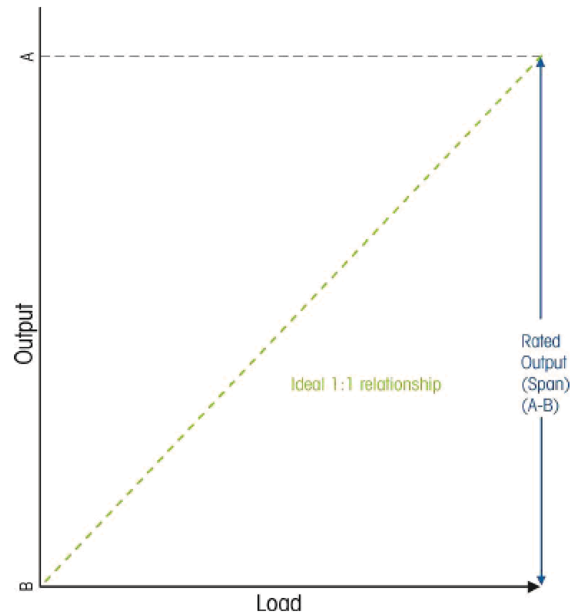

Figure 2: Compensated Calibration Curve

Traditional analog compensation involves measuring a load cell's output under different defined conditions of temperature, time, and load. Adjustments are then made to the strain gage's electrical circuit to correct errors in the measurements. This process can be difficult and time consuming, and there are limits to what it can achieve. This limited error-correction technique is the method used currently for analog strain gage load cells.

A core competency of METTLER TOLEDO is a technique called digital compensation. Originally called DigiTOL®, this technique was pioneered in the early 1980s by Toledo Scale. To make digital compensation possible, each load cell is equipped with an analog-to-digital converter, microprocessor, and EEPROM. The microprocessor is programmed with a variety of digital compensation algorithms that adjust the load cell's output, cancelling out the effects of internal and external influence factors. As long as the effects are constant and repeatable, they can be compensated for quickly and easily.

It is important to note that the digital compensation described in this paper is used only for METTLER TOLEDO POWERCELL® load cells. There are many load cells on the market that are described as "digital." These products are compensated by traditional analog methods, after which the analog signal is converted to a digital signal. Their performance is no better than that of a typical analog cell. Digital junction boxes provide no significant performance improvement. The performance of the analog load cell remains the same, although there is a small benefit because the analog-to-digital processing occurs closer to the load cell.

Like analog compensation, digital compensation starts by measuring a load cell's output under different defined conditions of temperature, time, and load. But instead of adjusting the strain gage's electrical circuit, the microprocessor then adjusts coefficients in the digital compensation algorithms.

Compensation

The primary digital compensation algorithms are

- Linearity
- Hysteresis
- Temperature Effect on Zero Balance
- Temperature Effect on Span (Gain or Sensitivity)
- Creep

Digital compensation is better than analog compensation at accurately matching the physical phenomena that a load cell measures. Analog zero temperature compensation normally applies one rate of correction over the entire temperature range. Digital compensation can apply one rate of correction in the lowest temperature range and other rates at higher ranges. It can also be adjusted over a greater range that is not limited by the material properties of the load cell or the compensating circuit. Digital compensation takes into account the interaction of multiple influence factors such as time and temperature for creep, which normally are not adequately compensated in an analog load cell. Another reason digital compensation is more accurate is that digital circuits provide finer resolution. Analog compensation devices are produced in general, or discrete, values and might not be available in the desired value. For example, analog devices might use a 50Ω resistor when a 50.6Ω is really required. Finally, because analog compensation resistors are sensitive to temperature, they can introduce unwanted error into the circuit they are intended to compensate. With digital compensation, no unwanted error is introduced.

Linearity Compensation

Linearity measures a load cell's ability to produce accurate weight signals throughout its weighing range as the load is increased. A perfectly linear load cell is represented by the straight line on the graph in Figure 3. When there is a linearity error, a scale reads correctly at zero and at full capacity but incorrectly between those two points. The weight indication can either drift upward and read higher than the actual weight (as shown in the graph) or drift downward and read lower than the actual weight.

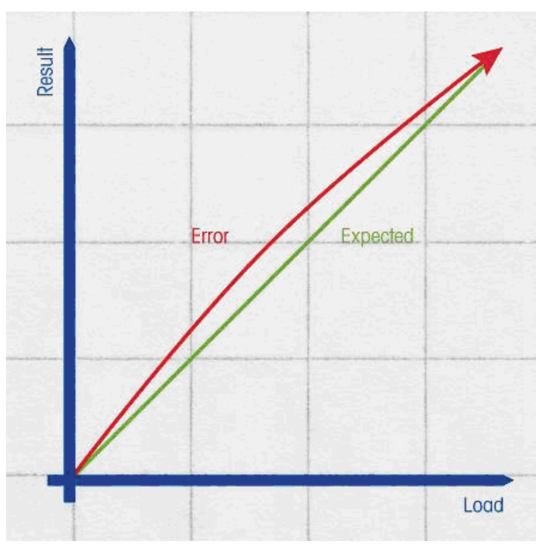

Figure 3: Linearity Error (Increasing Load)

Readings of a known force applied over the capacity range are used to calculate the linearity coefficients along the "expected" plot (Figures 3 and 4) to achieve the desired results shown in Figure 2. The coefficients used in the digital compensation algorithm are calculated from these readings. The algorithm operates by applying a correction to the load cell's output based on the actual load applied.

In an analog system, linearity is compensated by summing the load cells and adjusting the linearity inside the weighing terminal. If a load cell is exchanged in an analog system, linearity would be unknown until test loads are applied to the scale to re-establish linearity.

Hysteresis Compensation

A good explanation of the phenomenon called "hysteresis" is found in a paper entitled *Hysteresis Compensation,* written by Dr. Neil Griffen in November 1989. The following paragraphs are an excerpt from the paper:

> Most transducers exhibit a property called hysteresis. Hysteresis or as it is sometimes called "internal friction" appears in the output of a transducer when a series of loads are applied and then removed. Comparing the readings as the loads are removed with the readings, at the same load, as the loads are being applied results in a difference. This difference is called hysteresis. Generally speaking it is positive although some cases of negative hysteresis have been demonstrated. In strain gage based transducers this effect can be quite large and often limits the overall accuracy of the device.
>
> The effect rises primarily from the material properties and geometry of the transducer. All counterforce materials whether metal or glass/ceramic exhibit hysteresis to varying degrees. Epoxy based strain gages also exhibit hysteresis and contribute significantly to the overall hysteresis seen in transducer outputs.
>
> The most common way to improve hysteresis has been to improve the quality of the counterforce material. Many ceramics, for example, exhibit little hysteresis but are often expensive and subject to other manufacturing difficulties. By varying the production parameters and heat treat procedures of some metals, the hysteresis can be improved to acceptable levels for high accuracy applications but usually cannot be removed completely.
>
> Little has been done to improve the hysteresis due to the gages themselves. Other sensors such as vibrating wires or capacitors may not have hysteresis problems but it will appear in the output as it is still in the counterforce material.
>
> It should also be noted that many times hysteresis arises from the method of mounting or applying the load to the transducer. Here there is often a slippage or movement between the load cell and the scale structure that appears as hysteresis.

Hysteresis compensation reduces the curve shown in Figure 4 so that the load cell output is closer to the ideal straight line.

The hysteresis coefficients used in the digital compensation algorithm are calculated from a series of weight readings for a known force applied over the capacity range.

The algorithm corrects the load cell's output based on the actual load applied and whether the current load is greater or less than the previous load applied. This procedure is fairly simple when the load is applied and removed in one step. It becomes much more complicated when the load is applied and removed in a series of unequal, increasing/decreasing steps. As a result, the hysteresis algorithm is quite complex and patents do exist.

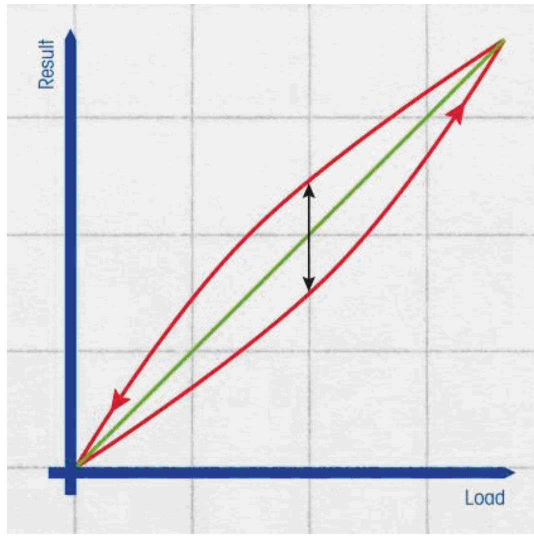

Figure 4: Hysteresis Error

Temperature Dependent Compensation

Temperature is the most significant external influence factor. A load cell's primary components (counterforce, enclosure, and strain gage) are made of metal. As the temperature changes, the expansion and contraction of the metal causes strain in the load cell. A strain gage cannot tell if the strain is due to an applied load or thermal expansion and contraction. Under controlled conditions, the effect of temperature can be isolated and measured. Since the effect is constant and repeatable, it can be compensated. To develop correction coefficients, load cells are tested throughout the temperature range, measurements are recorded, and temperature-related deviations are adjusted to obtain the expected result. The correction coefficients are stored in the load cell's permanent memory.

Temperature affects other factors that require compensation: zero balance, span (or sensitivity), and creep.

Zero Balance Temperature Compensation

Zero balance is the measured output at zero applied load. Compensation of temperature effect on zero balance is achieved through an algorithm, which yields identical zero readings at varying temperatures. If the calibration curve of Figure 1 were represented by the formula $y = mx + b$, then zero balance temperature compensation applies to the y-intercept b.

Zero compensation is determined by taking zero load readings throughout the operating temperature range. The coefficients used in the digital compensation algorithm are calculated from these readings. The algorithm operates by applying a correction to the load cell's output based on the actual temperature of the load cell.

Span Temperature Compensation

Span is the sensitivity of a load cell to applied load (the difference between an applied load reading and a zero load reading). Span temperature compensation involves correcting the span values obtained throughout a temperature range so that the net change in the weight reading when an identical load is added will be the same at any temperature. In other words, the output of a load cell at a given load is always the same at any temperature. If the calibration curve in Figure 1 were represented by the formula $y = mx + b$, then span temperature compensation applies to the slope m.

Span temperature coefficients are determined by applying identical forces to a load cell at different temperatures. The coefficients used in the digital compensation algorithm are calculated from the weight readings. The algorithm operates by applying a correction to the load cell's output based on the actual load applied and the actual temperature of the load cell.

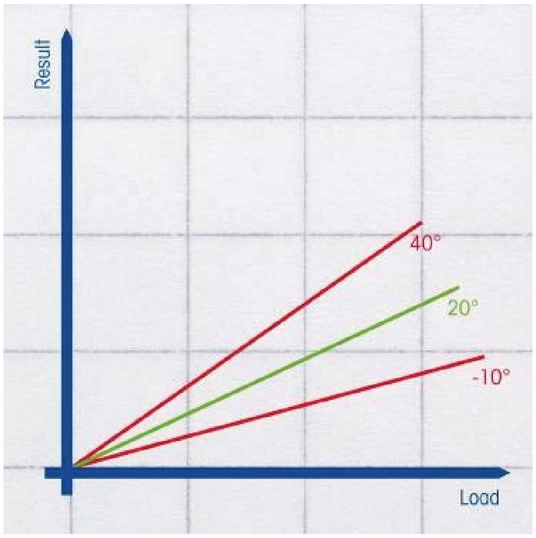

Figure 5: Span Temperature Influences (Independent of Zero T° Influence)

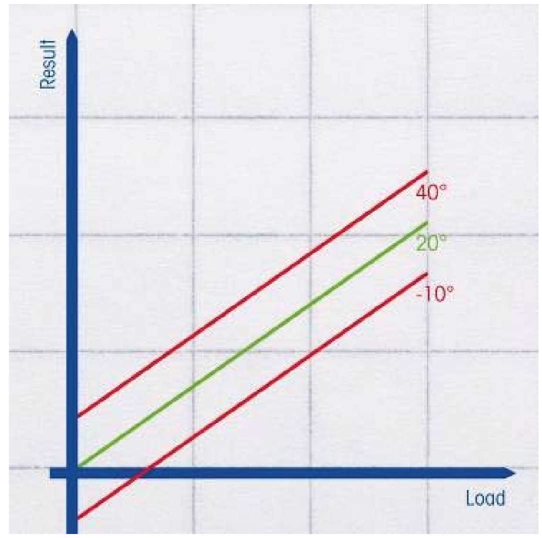

Figure 6: Zero Temperature Influences (Independent of Span T° Influence)

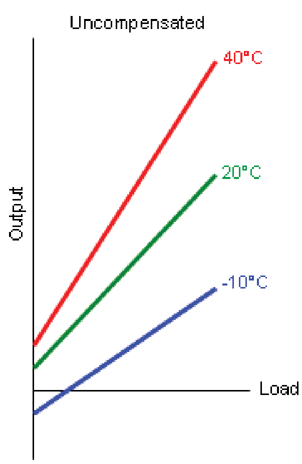

Figure 7: Uncompensated Cell (Both Span and Zero Influence)

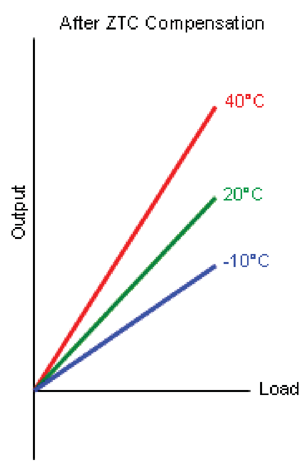

Figure 8: Following Digital Zero Temperature Compensation

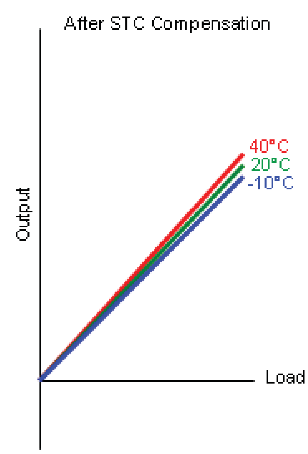

Figure 9: Following Digital Span Temperature Compensation (Lines are Separated for Clarity)

Creep Compensation

Creep is an increase or decrease in load cell output for an applied load over time. For example, the weight reading for a truck parked overnight on a scale would tend to change due to creep. Under an applied load, a load cell's metal components continue to stretch. To complicate things further, the rate of stretch over time depends on the temperature. This continued stretching over time causes additional strain in the load cell. A strain gage cannot tell if the strain is due to an applied load or creep. Under controlled conditions, the effect of time under load can be isolated and measured. Since the effect is constant and repeatable, it can be compensated.

Creep coefficients are determined by applying an identical force to a load cell at various temperatures for a defined period of time. The coefficients used in the digital compensation algorithm are calculated from the readings.

The algorithm operates by applying a correction to the load cell's output based on the actual load applied, the actual time the load has been applied, and the actual temperature of the load cell. This procedure is fairly simple when the load is applied and removed in one step. It becomes much more complicated when the load is applied and removed in a series of unequal steps with various time intervals between steps. As a result, the creep algorithm is quite complex and patents do exist.

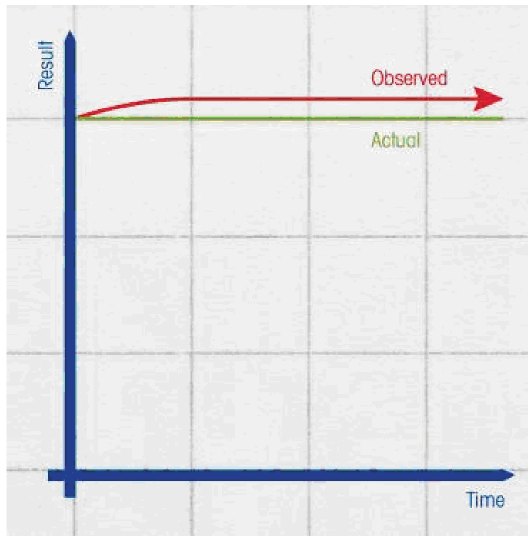

Figure 10: Creep Influence

Summary
Load cell accuracy is reduced by the sensor material, temperature, and applied load. Most analog load cells are compensated by adjusting discrete components in the analog circuit to achieve in-tolerance results. Higher results are not achievable because of the tolerances and limited ranges within the circuits and the amount of effort required.

Better results can be achieved with digital compensation, which allows more precise adjustments of constant and repeatable errors. The greater accuracy of digital compensation leads to cost savings that can be significant, depending on the value of your goods and your desire to reach your quality targets.

Definitions

Accuracy: The capability of a measuring device to provide measured values without systematic measurement deviations.

Creep Error: The time-dependent error when a load has been placed on a weighing surface for more than 30 minutes. Creep compensation attempts to minimize the effect of this phenomenon.

Hysteresis (Error): The path dependency observed when placing and recording the observed values of test masses on a measuring device and then reversing the action and measuring the difference between the positive and negative paths. **Hysteresis compensation** attempts to restrict the error to the expected value. It is important to note that hysteresis is material dependent and therefore difficult to correct using analog methods.

Linearity: A measure of how well the sensor/scale is capable of following the linear relationship between the loaded weight and the display value. The characteristic curve of the measuring device is a straight line between zero and maximum load. **Non-linearity** defines the width of the band within which there can be a plus or minus deviation of the measured value from the ideal characteristic line. **Linearity compensation** attempts to correct the non-linearity in an effort to match the linearity curve. In analog scales, linearity correction does not occur in the load cell, but in the junction box or terminal. Digital compensation at the load cell can generally eliminate cell-based non-linearity; the remaining non-linearity would then result from the weighing device or the substrate on which it is mounted or placed.

Non-repeatability: The deviations observed when multiple measurements are taken using the same test load/ mass under unchanging influence factors.

Span Temperature Error: The deviation from the ideal condition at load which is directly correlated to the temperature at the time the measurement was recorded. This error can be observed at any point throughout the range of the scale. Span compensation attempts to hold the test value to the ideal linearity plot within an agreed tolerance, throughout the defined temperature range.

Zero Temperature Error: The deviation from the ideal condition at zero which is directly correlated to the temperature at the time the measurement was recorded. Zero compensation attempts to hold the zero value, within an agreed tolerance, throughout the defined temperature range.

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