## Application Note 20171020

# How Strain Gage Torque Sensors Work

During almost 80 years of service, strain gages have proven to be remarkably accurate and reliable mechanical load sensors. They now dominate weighing including static, dynamic, precision and legal for sale applications. They are also used in the vast majority of precision torque sensors. All Himmelstein torque sensors are strain gage based. The simplest torque sensor is depicted in figure 1 below. When torqued, the element is stressed in shear – on a plane through the shaft, perpendicular to the shaft axis. The shear stress creates equal magnitude tensile and compressive stresses at 45 degrees to the shaft axis. Strain gages are installed at 45 degrees to the shaft axis and sense those tensile and compressive stresses.

The equations that relate shaft torque ($T$), shaft stress, shaft dimensions and shaft material are:

For a round shaft: $$\text{Stress} = \frac{16T}{\pi d^3} \qquad [1]$$

For a square shaft: $$\text{Stress} = \frac{T}{0.208a^3} \qquad [2]$$

When torque is in lbf-in units, dimensions in inches,

Figure 1.

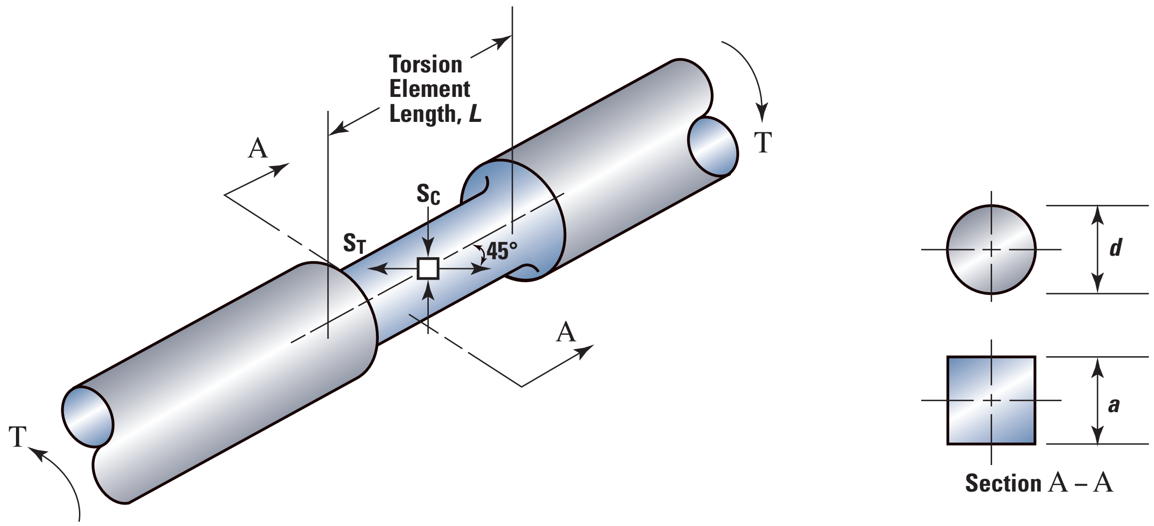
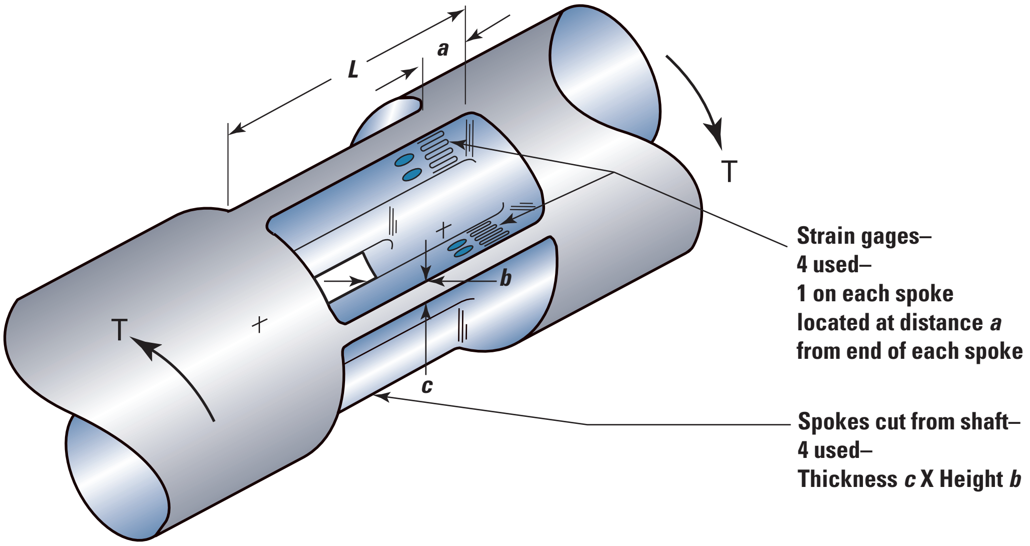


Figure 2



**Strain gages–**
**4 used–**
**1 on each spoke**
**located at distance *a***
**from end of each spoke**

**Spokes cut from shaft–**
**4 used–**
**Thickness *c* X Height *b***

then stress is pounds/square inch (psi). Where G is the material shearing modulus, the sensor's angular deflection in radians is:

For a round shaft: $$\theta = \frac{32TL}{\pi G d^4} \qquad [3]$$

For a square shaft: $$\theta = \frac{TL}{0.1405Ga^4} \qquad [4]$$

A square shaft has the advantage of gaging on a flat surface and allows connecting wires and solder joints to be placed in low stress areas, i.e., at or near the corners. Round and square torsion elements are not used at low torque levels because the gaging area becomes impractically small and the element deflection, as determined by equations 3 and 4, becomes unacceptably large, i.e. the element stiffness is too low. To overcome these issues, the torsion element depicted in figure 2 is used. Its beam stress is governed by equation 5.

$$\text{Stress} = \frac{3T(0.5L-a)}{bc^2\tau_{avg}} \qquad [5]$$

There are many variations of these designs. For example, hollow round shafts and radial spokes are often used. However, they all operate on the principles described above. Furthermore, the same elements are used for reaction (non-rotating or static) and rotating (or dynamic) sensors. In any case, a minimum of four strain gages are connected in a bridge, as shown in figure 3. When applied torque is zero, all four strain gages have the same resistance, the bridge is balanced and its output is zero – a very desirable result. Sophisticated sensors employ multiple bridges to cancel the effects of extraneous loads, temperature gradients, etc. Himmelstein uses as many as 32 gages in a number of elegant, standard designs.

The deflection in radians of the Figure 2 element is expressed by equation [6] below where the modulus of elasticity is ε.

$$\theta = \frac{TL^2}{4r_{avg}\varepsilon bc^3} \qquad [6]$$

Properly installed strain gages are subjected to the same strain as the structure to which they are bonded. Thus, where stress is τ, modulus of elasticity ε, Poisson Ratio is v, the strain the gage sees is:

$$\text{Strain} = \frac{\tau}{\varepsilon}(1+v) = \mu \qquad [7]$$ for the round and square elements with shear gages

$$\text{Strain} = \frac{\tau}{\varepsilon} = \mu \qquad [7a]$$ for the Figure 2 element with linear gages

When torque is applied, the change in gage resistance divided by the zero torque gage resistance is:

$$\frac{dr}{r} = (\text{Gage Factor})\ \mu \qquad [7]$$

The output of a 4 active arm bridge in mV per volt of excitation (mV/V) is:

$$1000\ \mu\ (\text{Gage Factor}) \qquad [8]$$

The bridge must be excited and readout which dictates a minimum of 4 connections – easily accomplished with a non-rotating sensor. For a rotating sensor the simplest "solution" is to use a slip ring assembly. Slip ring/brush assemblies wear and require maintenance; the wear products shunt the gages and produce zero drift, span errors and shunt calibration errors. Slip rings limit high speed operation and produce noise from brush bounce at all speeds. For these reasons Himmelstein does not make, nor will it ever make, a slip ring torque sensor.

Himmelsteins' first rotating torque sensors used rotary transformers to connect the rotating bridge to the stationary world without physical contact; see figure 4. These devices employed stationary carrier amplifiers to excite and readout the bridge via the rotary transformer. Carrier

Figure 3

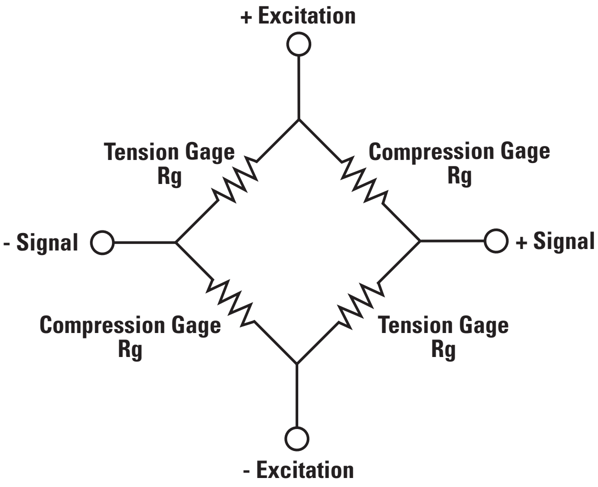
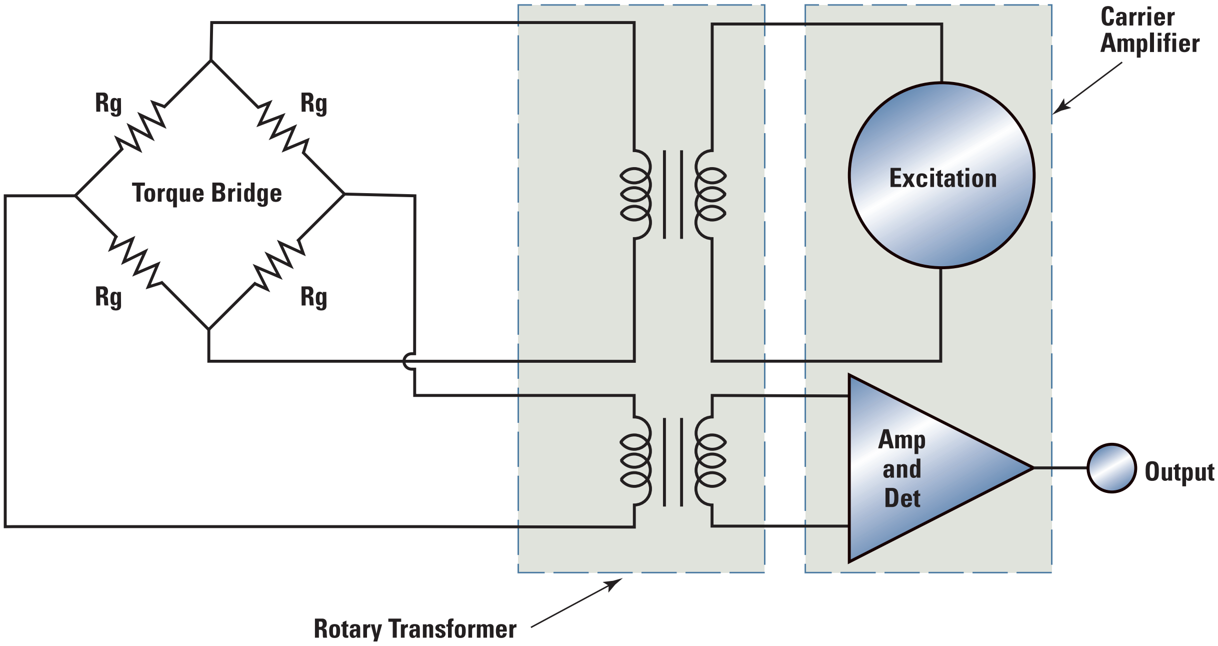


Figure 4



amplifiers don't drift and have greater immunity to noise than dc amplifiers; they only respond to in-phase carrier frequency signals. They are immune to low frequency signals (thermocouple voltages, power line frequencies, homopolar voltages, etc.) and to most high frequency signals. The result is a superior device that doesn't wear and require maintenance and which provides very high accuracy over long time periods.

However, *if the length of the interconnect cable is changed or altered in a significant way*, then the system must be re-calibrated to preserve *its initial accuracy*. To eliminate this cable dependency, Himmelstein introduced rotary transformer coupled Torquemeters with on-board carrier amplifier signal conditioning. All MCRT® series 48000V, 49000V, 59000V and 79000V have this feature and their accuracy is independent of the interconnect cable length, and construction.

Modern Himmelstein Rotary Transformer coupled Torquemeters have low phase shift, high immunity to external noise and to magnetic fields from eddy current brakes and large electric machines. Their high performance is due, in part, to use of alloy steel rotor *and* stator magnetic structures, not ferrites.

Competitive products use ferrite magnetic structures which saturate at a quarter of the field strength of Himmelsteins' alloy structures. That makes them less accurate in industrial environments. Ferrites have very low tensile strength, less that 10 percent of high strength alloys. As a result they are easily damaged by centrifugal stresses or impact shock. A number of competitive products *omit rotor magnetic structures* in order to better tolerate shock and high centrifugal stresses. That compromises the transformer's noise immunity, bandwidth and signal handling capabilities.

## MCRT® 84000V and 85000V Ultra-Precision Bearingless Torquemeters (Bulletin 8701)

| | |
|---|---|
| **Ranges:** | 250 to 100,000 lbf-in (28 Nm to 11.3 kNm) |
| **Speed Rating:** | Model dependent; see specification |
| **Overload:** | 400% and 200% of full scale |
| **Signal Outputs:** | Shaft Torque, Rotor Temperature and Rotor Speed<br>**Torque:** ±10V or ±5V Analog, FM and Digital (RS232/422/485)<br>**Temperature:** Digital (RS232/422/485)<br>**Speed:** Pulse Train |
| **Overrange:** | 300% and 150% |
| **Combined Error:** | Three grades; 0.01%, 0.02% and 0.04% |
| **Zero Drift:** | 0.0003%/per deg. F. |
| **48 Hour Drift:** | ±0.02% of full scale |
| **Torque Sampling:** | 50 µs per sample |
| **Max/Min Update:** | 50 µs |
| **Shunt Calibration:** | True bi-directional rotor shunt calibration invoked by stator switches, I/O lines or computer command |
| **Rotor-Stator Transfer:** | 1.25 Mbaud |
| **Rotor-Stator Gap:** | Axial ±0.4" (±10.2 mm), Radial 0.3" (7.6 mm) |
| **Torque Processing:** | In addition to instantaneous torque data the user may select Maxima, Minima, or Spread data, select any of 13 constant delay signal filters with cut-off frequencies from 0.1 Hz to 1 kHz in 1-2-5 steps + 3 kHz, select any of 10 units of measure without re-calibrating, invoke tare, zero or hold and more. |

The latest, most accurate, Himmelstein Torquemeters are digitally based; both rotating and non-rotating reaction types. On the rotating types, both power and signal connections are non-contact made via integral rotary transformers. The torque signal is digitized on the rotor and transmitted as digital data to the stator where analog and frequency (model dependent) signals are created and output along with the digital data. They employ *true bi-directional rotor shunt calibration.* Many use rotating carrier amplifiers for low noise torque signal processing. Some output conditioned shaft speed and shaft power signals and most include powerful signal processing functions. All signal processing is microprocessor based; most devices boast five microprocessors.

Rotating Torque Sensors with Combined Errors as low as 0.01% are standard. Both bearing supported and Bearingless types are available in single range and dual range models. Standard models have Overload capacities of 200%, 400% and 1,000% of rated torque. All have at least 150% Overrange; typical Combined Error in the Overrange region is 0.04% of full scale; guaranteed maximum is 0.1%. *Overrange is critically important in avoiding errors from clipped peaks when the shaft torque is near sensor full scale.*

Standard products are available with torque ranges form 10 ozf-in (0.07 Nm) to 4,000,000 lbf-in (452 kNm) in many useful mechanical configurations. All products are calibrated bi-directionally to their full capacity in our ISO/IEC 17025.2005 accredited laboratory. Two of these devices are described below. The listed Bulletin contains complete specification and more extensive information. It can be found at our website; www.himmelstein.com.

## MCRT® 48800V and 49800V Ultra-Precision Shaft Style Torquemeters (Bulletin 7409)

| | |
|---|---|
| **Ranges:** | 25 to 375,000 lbf-in (2.8 Nm to 42.4 kNm) |
| **Speed Rating:** | Model dependent; see specification |
| **Overload:** | 400% and 200% of full scale |
| **Signal Outputs:** | Three; Shaft Torque, Shaft Speed and Shaft Power simultaneously available<br>**Torque:** ±10V or ±5V Analog, and Digital (RS232/422/485)<br>**Speed:** ±10V or ±5V Analog, and Digital (RS232/422/485)<br>**Power:** ±10V or ±5V Analog, and Digital (RS232/422/485)<br>(Analog output may be configured as single ended or differential) |
| **Overrange:** | 300% and 150% |
| **Combined Error:** | Two grades; 0.02%, and 0.04% |
| **Zero Drift:** | 0.0006%/per deg. F. |
| **48 Hour Drift:** | 0.02% of full scale |
| **Signal Sampling:** | Torque = 128 µs, Speed = 1.25 ms, Power = 128 µs |
| **Max/Min Update:** | 128 µs |
| **Power Calculation:** | 7,800 times per second |
| **Shunt Calibration:** | True bi-directional rotor shunt calibration invoked by I/O lines or computer |
| **Signal Processing:** | In addition to instantaneous data the user may select Maxima, Minima or Spread of Torque, Speed and Power Data.<br>Select any of 13 constant delay signal filters in 1-2-5 steps with cut-off frequencies from 0.1Hz to 1kHz.<br>Select from 33 units of measure without re-calibrating.<br>Invoke Tare, Zero or Hold data and more. |

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