ROTATING TRANSFORMER COUPLED TORQUE SENSORS

ELECTRICAL, MECHANICAL, & PERFORMANCE CONSIDERATIONS

The commonly used rotating shaft torque sensors available for precision test and measurement employ bonded foil strain gage technology as the basis for the torque measurement. On rotating shaft applications, various methods are utilized to provide excitation power input to the Wheatstone bridge and collect the resultant signal output. The various methods include; Slip Ring, RF Telemetry, IR Optical coupling, and Rotating Transformers. Each method has inherent advantages and disadvantages, but the fundamental accuracy of the strain gage bridge on the sensor shaft remains the same for each. Therefore the selection of one technology over another rests on application and end user requirements. Generally, the criterion for each application falls within the best compromise of compatibility with existing signal conditioning instrumentation, maintenance issues, reliability, and price.

This discussion will provide technical analysis of the various techniques employed to magnetically couple a rotating torque shaft sensor via transformers and ignores the individual application aspect.

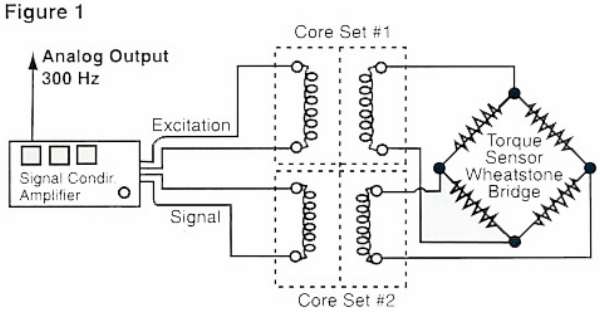
Five major areas of concern will be addressed:

- Random Noise
- Cable Length
- Low End Measurement Accuracy
- Shunt Calibration Transfer
- Mechanical Considerations

Transformer Coupling Techniques

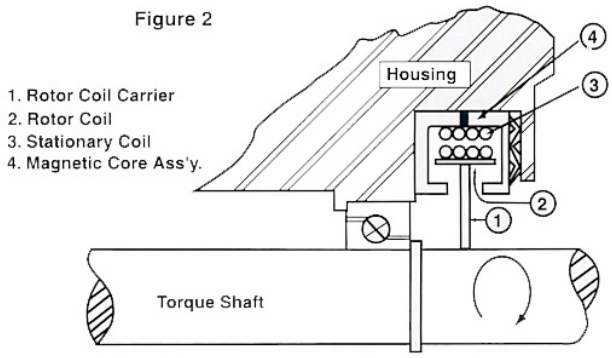
Figure I demonstrates the concept of transformer coupling to the strain gage shaft.

Figure 1



There are two (2) techniques employed in the manufacture of rotary transformers to varying levels of success. The first method, shown in **Figure 2**, is the concentric wound coil set (one stationary and one rotating), surrounded by a high permeability core (generally a ferrite material) to concentrate the flux in a magnetic path and improve coupling between the coils. A mechanical opening allows the rotating coil to have access to the stationary member (see **Figure 2**, items **2** & **3**). Controlling this "gap" figures very heavily in transformer efficiency and performance.

Figure 2



An alternative method, Figure 3, uses laminated "U-Core" (flux) concentrators to accomplish the transformer coupling. A circular lamination in the stationary sensor housing fixes the location of the signal and excitation stationary stator coils. A large mass armature of non-magnetic material, fixed to the torque shaft, carries an open face signal & excitation rotor assembly. This configuration has a significant "gap" to overcome, with resultant efficiency issues to accommodate. Additionally, all surrounding structure must be of either non-magnetic or paramagnetic material or the transformer efficiency further degrades. This usually mandates an aluminum housing and a sensor shaft of stainless steel, K-Monel, or some other less than desirable transducer grade material.

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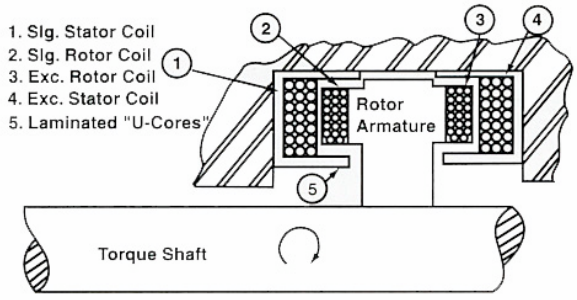

Figure 3

Random Noise

A rotary transformer operates precisely on the same principle as any conventional transformer, except that either the primary or secondary coils are rotating. In strain gage torque sensor applications, two (2) transformers are required; one (I) for excitation of the bridge, the other for transmitting the signal. As with any transformer, an AC current is required to power the system. The precise nature of the torque measurement demands a highly regulated carrier frequency to accomplish this.

This regulated frequency allows the use of a synchronous demodulator, providing an inherent advantage against electrical noise, especially at low end measurement, that plague many DC based systems. However, due to carrier amplifier design requirements, the overall bandwidth is limited to about 10% of the carrier frequency. Most US systems use a 3.277 kHz carrier with the analog output signal rolled off at 300 Hz. Electrical noise is always present, and affects performance (signal-to-noise ratio) in two (2) distinct areas:

- Magnetic susceptibility and E-Field induced noise.
- Conducted noise (cable induced).

Magnetic susceptibility begins once an entrance "gap" to the core set is made to accommodate the rotor coil. The larger the "gap" the more the magnetic "flux fringes" reduces transformer efficiency. This allows E-Field noise to enter the transformer coil set. Any magnetic

Random Noise (continued)

susceptible metal contacting the ferrite core set aggravates this problem. In addition, the ferrite material, being a high stress, brittle material can be damaged in a vibration application. The SensorData design has virtually eliminated Magnetic Susceptibility by the removal of any direct magnetic field path to the core set (transformer). This approach allows the avoidance of exotic (expensive) shaft and housing materials and/or ceramic bearings to isolate the transformers, making the sensor easier to use in the field, more durable against vibration, bearing fretting, and end play problems, while remaining cost effective.

Conducted noise, as typically induced via the instrument cable, is the other factor. A fully differential transformer is most suitable to maximize the signal to noise ratio. However, previous competitive designs center tapped (tied to ground) the transformer winding to establish a zero reference on the signal side of the transformer. This technique compromises noise rejection and has been found the most damaging in applications with flux vector drive machines. We have designed around the fully differential transformer approach for maximum noise rejection.

Cable Length

SensorData employs a lower inductance value in the excitation and signal transformer than competitive units, allowing for longer cable lengths (higher overall capacitance). Using the recommended 7 wire configuration, with the shunt cal, and signal & excitation sensing leads, the practical limitation on field cable length is about 500 feet, while using a 3.277 Khz carrier excitation frequency. It is to be noted that using a different carrier frequency (say 5KHz) will alter this and reduce the cable working length. The instrument usually is the controlling factor in cable length. It must have a balanced excitation (both amplitude and phase) to accommodate cable length and not swamp out the "C" balance control. In general, when using cable lengths above 500 feet, resonance will occur, as well as the resultant instrument front end saturation.

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Low End Measurement Accuracy

SensorData design provides for full strain gage signal output (2 mV/V) at full scale. We utilize the natural step up transformer function to enhance the mechanical overload characteristics, and not to unduly amplify a weak sensor signal. Starting with a strong signal at the top end allows for an inherently stronger signal at the low end. The torque sensor is very linear mechanically, and this linearity is faithfully tracked to the low end. We have seen successful results down in the 5% of full scale region due to the inherent noise rejection of a highly regulated carrier signal, and the strong mV/V output from the bridge at the low end of the sensor.

Manufacturers employing segmented magnetic (flux) concentrators, are forced to deal with a low signal at the full scale, increasing signal to noise problems at the low end (below 20% full scale output). The technique of segmented magnetic concentrators results in an inefficient coupling of the transformer, requiring more turns thus lowering the signal/excitation through-put. This results in poor immunity to extraneous noise. On board amplifiers have been used to compensate this, but probably further worsen the problem. Amplifying a weak signal only masks the problem, showing up as amplified noise at the low end.

Shunt Calibration Transfer

The single most important factor in any transducer is the ability to provide an "in-situ" calibration, fully traceable to the NIST, or any other regulatory body. The technique of using a precision "Shunt Resistor" across one leg of the Wheatstone Bridge to perform this calibration has long been the accepted method in strain gage based sensors.

In rotary transformer coupled sensors, access to the bridge has made this method difficult to achieve, so a secondary "star" reference bridge has been built in to the transformer circuitry. This "easy" approach has generated much controversy. Because of the potential for temperature drift in various components in the

Shunt Calibration Transfer (continued)

star network and the strain gage sensor bridge, there has existed error in measurement accuracy during the time interval between when the shunt calibration is performed and after the test, when the star bridge and sensor bridge drifted at different rates. Elaborate schemes to remove the star reference and remotely reposition it from the sensor will not guarantee accurate tracking. The SensorOata "on-board" circuit guarantees the sensor signal is phase coherent with the calibration signal. This circuit is further refined by temperature compensation matching of the calibration network to the sensor. No remote circuit is employed. The most critical issue is the physical proximity of the circuitry to the sensor. Whatever the ambient test conditions the sensor is exposed to is precisely what the shunt transfer circuit is compensating for. We call this technique "WYSIWYM" (What You See Is What You Measure). This (along with other considerations, such as cable & instrumentation) assures"the calibration number is valid under a variety of real world conditions. SensorOata matches both to a tolerance of 0.00 1% per °F.

Mechanical Considerations

All SensorOata Rotary Transformer units are designed for minimal mass. Typically, by physical dimension and weight, these units are 1/3 the size of any other manufactured unit. The design philosophy was to enhance frequency response by: a) Reducing the physical size, thereby affecting the rotational inertia, due to weight reduction and the diameter reduction of the rotating components. b) Increase torsional stiffness, by reducing the overall length and the "spring element" section of the strain gage area. c) Reduce the overall size to make the intrusion of the torque sensor into the drive line as minimal as possible. This pushes shaft criticals up higher into speed areas where they are not a concern in most applications and often eliminates the need for foot mounting the sensor. This simplifies the customers' drive line installation.

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Foot mounting, although permissible and often used, has the potential to cause (2) problems:

- The potential for a noise coupling path (ground loop) is eliminated by not having a sensor housing tied to ground.

- A foot mounted sensor can unnecessarily cause bearing wear by axially induced force on the sensor shaft. Floated torque shafts do not see this problem. This problem is especially acute when the transformer technique, as depicted in **Figure 3**, is utilized.

Bearing speeds have been significantly increased over other, larger designs, by allowing for the selection of smaller bearing races. Bearing life is also positively affected. There is no need for exotic bearing materials, such as ceramic bearings for magnetic isolation, or Ail/Oil Mist combinations for speed enhancement. Also, the use of a steel housing eliminates the need for mounting bearings in a housing of dissimilar material, which can have disastrous effects in critical speed, vibration or temperature differenting situations.

As previously described, all ferrite material is mechanically isolated from any metal component, thereby providing for a superior vibration resistance.

The shorter length also has proven more forgiving in applications where bending moments are present. As with any rotating component, the proper selection of mechanical couplings is required. However, the sensor will inevitably see a bending moment upon each revolution, as temperature and wear changes occur, due to the normal running operation. The minimized length will enhance the bending moment resistance.

Summary

- The SensorData Rotary Transformer **Model 231**, **T250,** and **T260** Series all feature:
- Highly efficient concentric wound Core Sets for improved magnetic coupling.
- A low mass, torsionally stiff mechanical design, reducing rotating inertia and providing enhanced frequency response.
- A unique Core Set design to minimize magnetic susceptibility.
- Fully Differential Transformer wiring to eliminate conducted noise, enhancing the Signal to Noise ratio.
- Mechanical isolation of any vibration sensitive components for field rugged service.
- High output at full scale.
- Shunt transfer with true phase coherent temperature tracking to the strain gage bridge.
- Standard available grease pack bearings for low maintenance, with highest available standard speed rating.