DEVELOPMENTS IN CONTINUOUS TORQUE MONITORING COUPLINGS

Bill Meier
Project Engineer
Kop-Flex, Inc., Emerson Power Transmission

Dave Edeson
Product Engineer
Kop-Flex, Inc., Emerson Power Transmission

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Bill Meier
Kop-Flex, Inc., Emerson Power Transmission

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ABSTRACT

The use of continuous torque monitoring couplings is quickly becoming an integral part of many predictive maintenance programs in the petrochemical and process industries. More and more operating facilities are using instrumented torque-measuring couplings in order to know how their critical equipment is performing so that the intervals between scheduled shutdowns can be chosen appropriately. This paper will cover a brief history of torquemeters; i.e., the basic measuring types which are 1) strain gage types and 2) torsional deflection types. Discussed will be the theories of operation on how they work and the advances and limitations of these types. Included will be the accuracies that can be obtained by each one and the features of each. In addition, recent advancements in the electronic technology will be discussed.

INTRODUCTION

Performance Testing and Shaft Power Measurement

Field performance testing and monitoring is essential in turbomachinery to assess its current condition. For example, the objective of field testing gas turbine driven compressor sets is typically to verify acceptance criteria such as heat rate, specific fuel consumption, turbine shaft power, and compressor gas power. Generally, performance testing which is done to determine if the machinery meets the manufacturer’s guaranteed design points should be performed in the OEM’s test facility, where the accuracy of the instrumentation as well as the control of environmental factors is better.

Field performance testing has become most useful in establishing a baseline from which the machinery’s future health can be measured. Direct measurement of the shaft power between connected machinery enables one to isolate which machine is responsible for an overall decrease in output. Continuous on-line monitoring of the machinery’s output power provides operational trending data.

For example, over a period of time it is determined that for a given amount of steam into a steam turbine driving a cracked gas compressor train in an ethylene plant, the throughput of compressed gas has dropped 5%. Thus there is a 5% loss of efficiency. Where was the efficiency lost? Was it lost in the steam turbine or in the compressor? By measuring the torque in the coupling, the power output of the steam turbine is determined. Looking at a trend of the turbine shaft power will show whether the loss of efficiency occurred in the turbine by showing that the shaft power dropped 5%. If the shaft power remained constant, then the compressor efficiency must have dropped. With multibody compressor trains, a torquemeter coupling between each body will provide the data to show which compressor body has lost efficiency. Because time and resources are limited during any shutdown or planned turn around, by knowing which piece of machinery has lost efficiency, those resources can be allocated most efficiently.

Predictions in performance degradation can be made so that corrective action schedules can be established. A detailed history of the relative performance of the machinery is needed to accurately assess its condition. The accuracy of these field measurements is critical to the reliability of any predictive maintenance program. Factory testing of the equipment will typically involve smaller test uncertainties than field testing. During factory testing of gas turbines, for example, the shaft power is usually measured directly by coupling it to a dynamometer. Load cells measure the reaction forces on the casings to provide a direct measurement of torque so that shaft output power can be calculated as the product of measured torque multiplied by the operating speed. In field testing, however, unless a torque measuring coupling is used, the gas turbine shaft power is not able to be measured directly. It must be determined by performing a heat balance with the calculated gas power of the driven compressor, or by performing an energy balance on the gas turbine system. Using a torquemeter coupling can achieve almost a similar accuracy as the factory test method. The heat balance and energy balance methods are subject to significantly higher measuring uncertainties (Kurz, Brun, Legrand, 1999).

Heat balance and energy balance methods are dependent on measurements of pressures, temperatures, flows, gas compositions, and mechanical losses. Each of these measured parameters has its own instrumentation tolerance, which contributes to the overall test uncertainty. The largest instrumentation tolerance is due to gas composition (up to 5%), with other measurement errors due to pressure (up to 2%), flow (up to 2%), equation of state (up to 2.5%), and temperature (up to 4°F). If the shaft output power is known, the gas turbine heat rate and efficiency can be determined. If a torquemeter is used, the total uncertainty for the gas turbine power can be reduced to about 1 percent to 1.5 percent. (Kurz, Brun, Legrand, 1999). Without a torquemeter, the error can be as much as 7% (R.D. and J.D. van Millingen, 1991).

Similarly, the accurate performance measurement of a centrifugal compressor is very dependent on the quality of the field data. Again an important parameter is the shaft horsepower, which can be calculated directly if a torquemeter is available. Otherwise, a heat balance method is recommended, such as that given in ASME PTC 10 (1997). For example, Equations 1 and 2, (Wilcox, 1999) are the general formulas for calculating input shaft horsepower into a compressor. To get the shaft horsepower in this manner is filled with the attendant measurement tolerances (errors).

$$SHP = \frac{(\dot{m}_1 - \dot{m}_{S1})\ (h_2 - h_1) + Q_R}{2545} + HP_{MECH} \qquad (1)$$

$$SHP = HP_{GAS} + HP_{MECH} \qquad (2)$$

NOMENCLATURE

SHP = Shaft horsepower
m_1 = Mass flow into compressor (lbm/s)
m_2 = Mass flow out of compressor
h_2 = Specific enthalpy out of compressor (Btu/lbm)
h_1 = Specific enthalpy into compressor
HP_{GAS} = Compressed gas HP
HP_{MECH} = Mechanical HP losses dissipated through seals, bearings, etc.
Q_R = Radiative Heat Transfer

TORQUEMETER COUPLINGS

Methods Of Torque Measurement

The growing popularity of instrumented couplings for continuous on-line torque monitoring has led to the widely used term "torquemeter" couplings. There are several varieties of instrumented torquemeter couplings currently available. Each is capable of providing torque measurement through non-contacting means so there is no longer a need for the extra bearing supports associated with a "torquemeter" of years past.

These torquemeters physically measure the torque being transmitted between the two machines of which they are connected. Since they also measure the speed, the power transmitted between the machines can be calculated (torque multiplied by speed).

All torquemeter coupling designs are faced with the task of detecting a physical change due to torsion in the coupling while it is rotating, and getting this information to a stationary output device (generally in the control room). Over the years, many methods have been devised to measure the torsional effects exhibited by the coupling. These methods range from measuring changes in the acoustics of coupling mounted piano wires to the application of magnetic circuits which sense changes in permeability as the coupling winds-up. Most of these methods have fallen short of the accuracy required for meaningful use as performance monitoring instrumentation.

The challenge for accurate and reliable torque measurement is that each system is faced with determining those physical changes associated with torque alone while the coupling is subjected to a combination of torque, bending, thrust, centrifugal loads, and increased temperature (See Figure 1).

Discriminating the effects between these multiple loads has boiled down to two basic methods of detection:

1) Measurement of localized torsional **strain**, and
2) Measurement of overall torsional **deflection**.

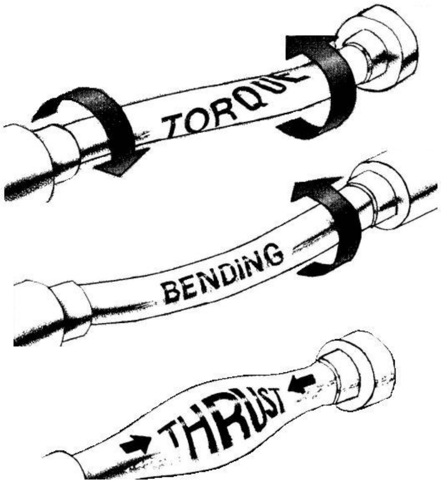

Figure 1. Torquemeters Must Decipher Torque Induced Effects From Other Combined Loads.

Strain Gage Type Torquemeters

There are several variations of the strain gage torquemeter system currently available. Each of them operates on the same general principle of:

1) Getting electrical operating power to the electronics and signal conditioning inside the coupling.
2) Feeding that power through a four arm strain gage bridge located on the rotating coupling.
3) Transmitting the resulting signal from the coupling back to a stationary receiver.

The strain gages are usually directly affixed to either the outside diameter or the inside diameter of a thinned down area on the coupling spacer (center spool piece). For slower speed applications, some manufacturers provide a clamp-on split collar which contains the strain gages. As torque is applied, the localized twisting in the area of the strain gages creates a signal by the unbalancing of the strain gage bridge. Since the coupling spacer will be exposed to axial, centrifugal, and misalignment loads in addition to torque, the strain gages of the Wheatstone Bridge (Figure 2) must be mounted precisely at 45° from the coupling's axis in order minimize the strains from these extraneous loads.

In the past, the method of transmitting power to and receiving signals from the rotating instrumented torque-measuring coupling involved the use of contacting slip ring arrangements. This rendered them useful for only low-speed, high-torque applications and presented problems related to wear and foreign particulates. Today, most strain gage torquemeter systems have overcome these problems by using non-contacting, electro-magnetic induction techniques. The basic strain gage type torquemeter (Figure 3) consists of a stationary component and a rotating component. Both components contain electronics. The stationary component (stator) provides power to the rotating component (rotor) via electromagnetic induction between windings contained on each component. The air gap between the stationary and rotating windings allows for relative axial, angular, and offset type excursions of the coupling during operation.

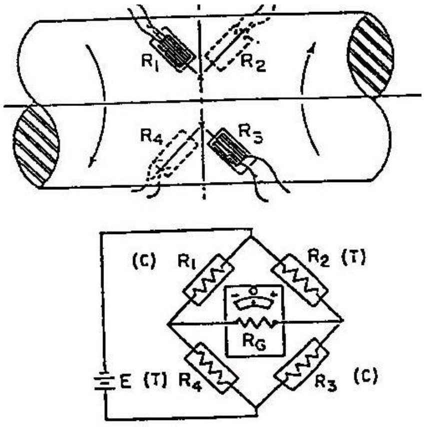

Figure 2. Wheatstone Bridge Used In Typical Strain Gage Torquemeters

The rotating electronics condition the power received from the stationary component and feed it through the strain gage circuitry. (The rotating strain gage circuitry is usually provided by the manufacturer with a protective wrapping due to the sensitivity of the circuitry to handling damage and possible chemical contaminates.). The output of the rotating strain gage circuitry is conditioned, amplified and transmitted back to the stationary component either by an FM (frequency modulated) signal, or by a second rotary transformer - depending on the manufacturer. For short term test applications and lower speed couplings, power may be supplied by battery packs that are strapped to the body of the coupling spacer.

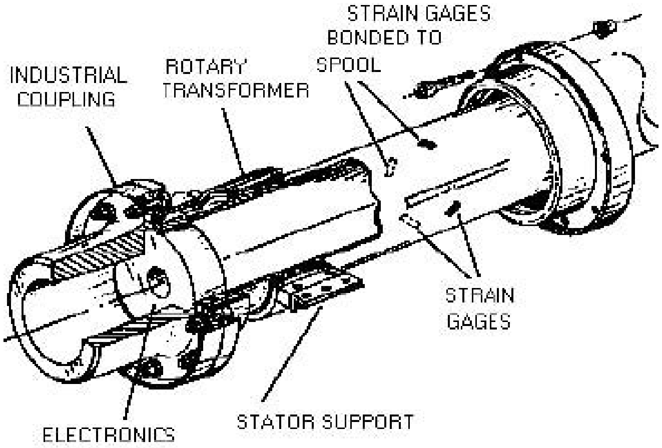

Figure 3. Typical Strain Gage Torquemeter Coupling

From the stationary component, the signal is typically sent back to the control room as an industry standard analog signal for connection to the user's data recorders or programmable logic controllers (PLC's).

Torsional Deflection (Phase Shift) Type Torquemeters

As with stain gage types, there are several variations of the torsional deflection torquemeter system currently available. Each of them operates on the same general principle of measuring the torsional "*wind-up"* experienced when the coupling is exposed to torque. This is done by comparing the relative displacement of one end of the coupling spacer to the other.

Using sensors to detect teeth mounted to each of the coupling creates electrical pulses. By timing the pulses relative to each other, also known as their phase shift, the torsional deflection can be measured by electronic systems. In this respect, *torsional deflection* torquemeters have become synonymous with *phase shift* torquemeters (Figure 4).

Each torquemeter is subjected to a factory calibration procedure. A measurement of its torsional stiffness is made so that the relationship of torsional deflection versus torque is accurately known. Also, a zero torque dynamic calibration is conducted so that the initial relative position of the teeth is known. This calibration data is programmed into the torquemeter electronics so that the torque being transmitted can be accurately calculated from the measurement of the torsional deflection.

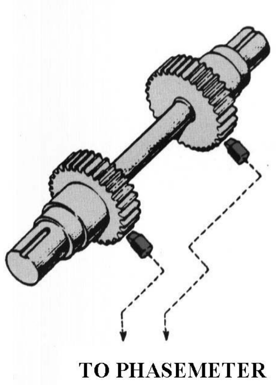

Figure 4. Basic Operating Principle Of Torsional Deflection Type Torquemeters

All phase shift type torquemeter couplings must find a solution to the problem that vertical and horizontal movements of the rotating coupling relative to the non-rotating pick-ups will produce an additional phase shift. The method of distinguishing between torsion induced phase shift and those caused by these lateral movements form the basic differences of torsional deflection torquemeter systems.

For phase shift type torquemeters the voltage signals sensed by the pick-ups are typically sent to the control room where the signals are then processed. As with strain gage type torquemeters, the output of the processing unit is also typically made available as an industry standard analog signal for connection to the user's data recorders or PLC's. All phase shift torsional deflection torquemeters measure coupling RPM as a byproduct of torque determination, so the torque and speed signals are typically multiplied for a direct readout of power.

Dual Channel Phase Shift System

One manufacturer deciphers genuine twist induced phase shifts from “false” laterally induced ones by providing a version of pick-up which senses the position of the toothed wheels around many points along the circumference of the coupling. Rather than supplying an array of circumferentially mounted speed pick-ups, each “pick-up” takes the form of an internally toothed ring. Each of these two pick-up rings (Figure 5) completely surrounds each rotating toothed wheel of the coupling. Each pick-up ring consists of circumferentially wound coils, which are then energized to create a toroidal flux path.

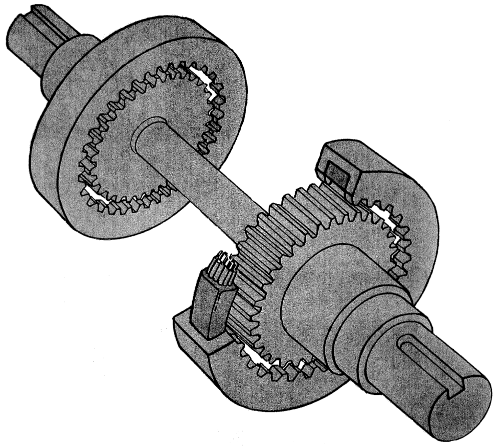

Figure 5. Pick-Up Rings Used in 2 Channel System

As the coupling “*lifts”* on one end relative to that pick up ring, the “*early*” signal on the front side of the coupling is canceled by an equally “*late*” signal at the back side of the same toothed wheel. In this way, the “average” circumferential position of teeth induces a sinusoidal voltage in the driving side pick-up ring (Channel A). Similarly, the average circumferential position of teeth induces a sinusoidal voltage in the driven side pick-up ring (Channel B). The processing unit receives these sinusoidal voltages of the “averaged” position of the driving wheel on channel A and compares it to the similarly averaged location of the driven wheel on channel B. The difference in phase of these two channels is a direct measure of torsional wind-up deflection. (Figure 6) By multiplying this torsional deflection by the predetermined coupling stiffness (measured during initial factory calibration), the processing unit is then able to determine the torque present in the coupling.

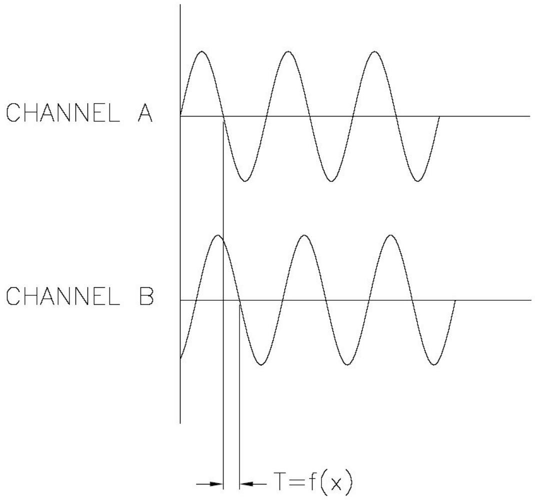

Figure 6. Determination of Torque by Change in Phase in 2-Channel System

3 Channel Phase Shift System

Another method of deciphering “twist” induced phase shifts from “false” laterally induced ones is to move the two toothed wheels of the coupling closer together to minimize the errors caused by lateral movements of the coupling relative to its housing. Simply shortening the length of tube between toothed wheels would not work, because it would result in a proportionally lesser amount of torsional twist.

Instead, the (first) toothed wheel which is to be moved closer to the (second) toothed wheel is still affixed to the coupling at the same axial location as the two channel system - but the manufacturer adds a non-torque carrying “reference” sleeve (Figure 7). The function of this reference sleeve is simply to translate the apparent location of the (first) toothed wheel, moving it closer to its paired (second) toothed wheel, without moving the location of the attachment point to the “torsion tube” underneath the sleeve.

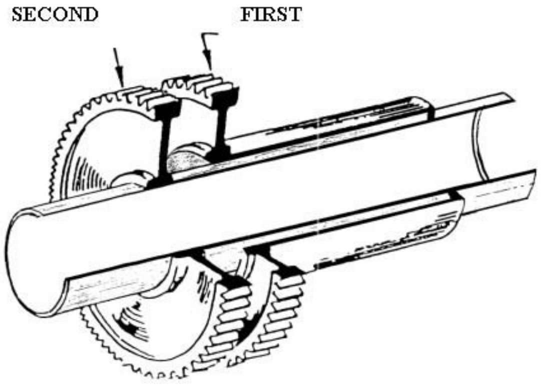

Figure 7. Basic Operating Principle of Reference Sleeve Used in 3 Channel System

In this arrangement, the reference tube is attached to the torque-carrying torsion tube at one end only. The attachment side is at the position of where the first wheel *would have been* if it had not moved over to the other side. The reference sleeve carries the first wheel to the other end of the coupling by cantilevering off its fixed end. By moving the axial location of the first toothed wheel closer to that of the second toothed wheel, the error of "false" laterally induced phase displacement is reduced, but since there is still some distance (x) between these toothed wheels, the error has not been eliminated.

This now "smaller" error is canceled by adding a third wheel (Figure 8). The third wheel is positioned exactly the same distance (x) from the second wheel, but on the opposite side of it. It is directly attached to the second wheel, so that any phase shift seen between the second and third wheel is attributable only to lateral movements (not from torque). In this way, as the coupling moves laterally within the housing – "earliness" of the signals for the first wheel can be canceled by subtracting the amount of the "lateness" of the third (compensating) wheel.

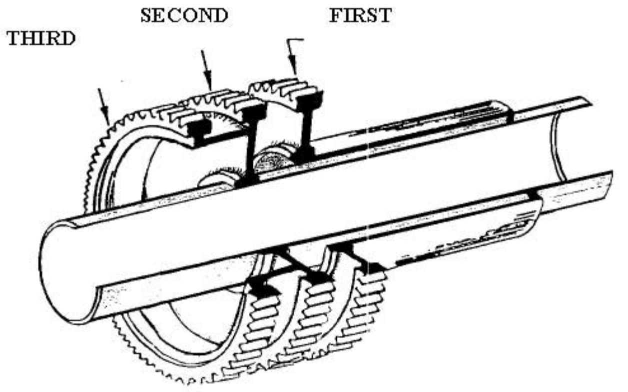

Figure 8. Three Channel Phase Shift System With Third Compensating Pick-Up

The sensor design is a standard variable reluctance sensor consisting of a wire coil wound around a permanent magnet. As each tooth passes through the flux field of the sensor, the processing unit receives a sinusoidal voltage of the average position of the driving (first) wheel on Channel A. Similarly, a sinusoidal voltage is received by the processing unit for the average position of the driven (second) wheel on Channel B. Likewise, a sinusoidal voltage is received by the processing unit on Channel C for the average tooth position of the compensating reference (third) wheel.

The processing unit (typically located in the control room) receives these sinusoidal voltages of the average location of the three wheels on channels A, B, and C. The phase difference between channel B and channel C is purely the laterally induced phase shift error. Knowing this, the processing unit subtracts this "error" phase difference from the phase difference between channel A and channel B. This "corrected" phase shift is then the value associated with torsional wind-up only.

As with the two channel system, the torsional deflection is multiplied by the predetermined coupling stiffness (measured during initial factory calibration), where the result is the torque present in the coupling.

Single Channel Phase Shift System

The single channel system is basically a modification to the three channel system. The one channel system brings the teeth associated with each end of the coupling spacer together in a single plane where they are detected by a single sensor. This gives rise to the term "*monopole"* system*.*

The way in which this is done is as follows. Like the three channel system, the one channel system moves the driving wheel of Channel A closer to the driven wheel of Channel B. Recognizing that the closer the two wheels can be made, the less the error associated with laterally induced phase shift. The wheels are moved close enough together that the wheels become *intermeshed* (Figure 9). This feature results in the elimination of the need for the other two channels (B & C), because the intermeshed teeth sense the tooth locations in a *single plane*. As the coupling moves laterally within its housing, relative lateral displacement of the two wheels is therefore eliminated. Wherever the coupling moves relative to the sensor, both sets of intermeshed teeth are in the same lateral position.

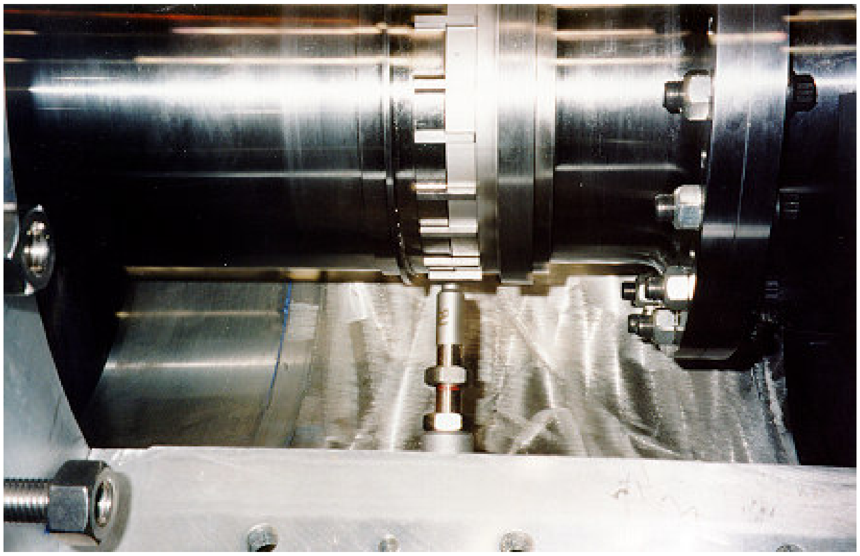

Figure 9. Intermeshed Teeth and Sensor of Single Channel System

With the single channel system, instead of determining the phase shift between two separate speed pick-ups, the phase shift is determined between consecutive pulses generated by a single sensor. As the coupling winds up due to torque, the relative spacing of the teeth changes. (Figure 10) The pulses generated by the sensor are sent to the processing unit where the relative timing of the pulses is measured. As with the two channel and the three channel system, the torsional deflection is multiplied by the predetermined coupling stiffness (measured during initial factory calibration), where the result is the torque present in the coupling. Since the coupling RPM is once again an indirect result of the frequency of the pulse signal, the processing unit is also able to directly calculate the power being transmitted by the coupling.

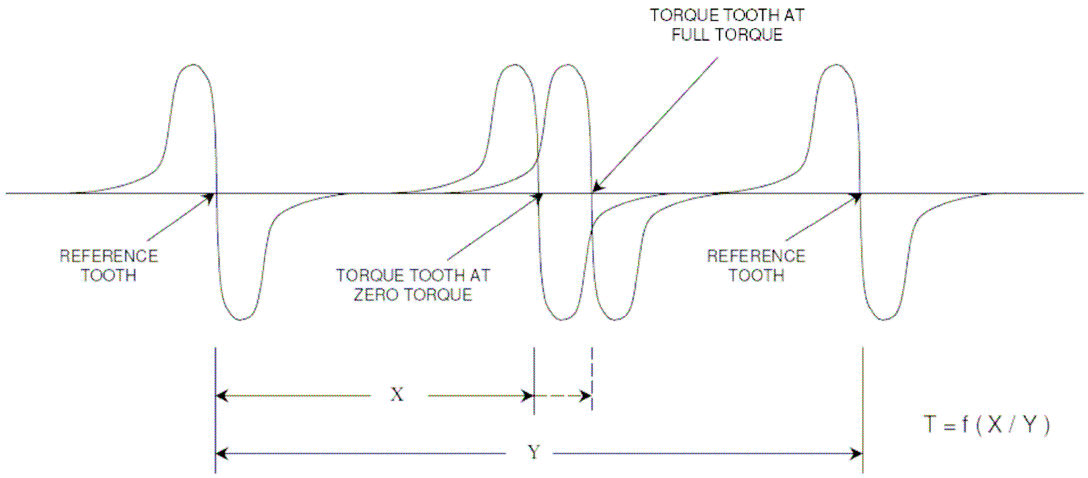

Figure 10. Determination of Torque by Change in Phase in 1-Channel System

The manufacturer of the *monopole* single channel system has also eliminated the radial support bearing that was often found at the free end of 3-channel systems. The purpose of this radial bearing was to eliminate any projected offset of the cantilevered wheel if the torsion tube underneath were to “bow” from misalignment. In such cases, a bearing was often used to restrain the free end from being allowed to become laterally displaced.

With the current single channel system, a second independent torque reading is taken on the same set of toothed wheels to provide redundancy for increased system reliability. By choosing the location of the redundant sensor to be on the opposite side (rear instead of front) of the tooth set, the need for a support bearing at the free end has also been eliminated. (See Figure 11). If the torsion tube underneath the reference sleeve “bows” under misalignment, any “lifting” of the free end of the cantilevered wheel will produce an early signal between consecutive pulses in the front of the coupling, with an equally late signal at the rear. Any difference found between these two independent phase shift measurements (remembering that each phase shift is determined via consecutive pulses on a single channel) is then attributable to a laterally induced “false” phase shift. The average phase shift of these two readings is the result of torsional wind-up alone.

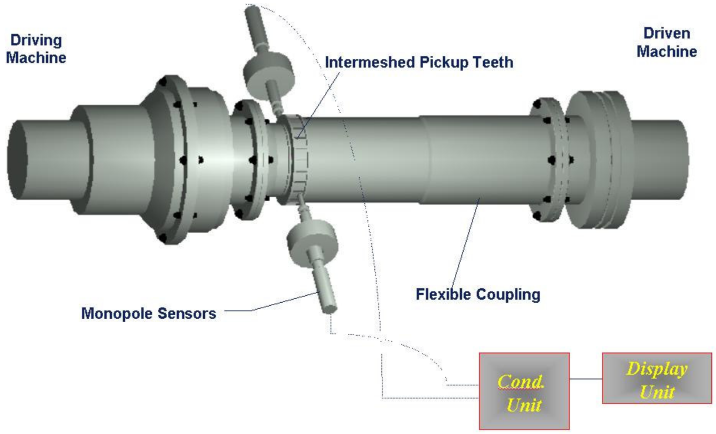

Figure 11. Single Channel System with Second Pick-Up

COMPARISON OF TORQUEMETER SYSTEMS

Each variation of a torquemeter system has its advantages and disadvantages. All torquemeter systems have additional weight compared to an ordinary, non-instrumented coupling due to the additional hardware that is associated with the coupling. The torquemeter coupling may also have a different torsional stiffness in order to have a measurable degree of twist or strain so that the electronics can measure torque accurately. None of this needs to be a problem if these factors are accommodated in the rotordynamic analysis of the turbomachinery system.

Strain gage based systems have electronics located within the coupling. This location exposes the sensitive electronics to potentially detrimental environmental factors such as heat, hazardous gases, and extreme centrifugal forces. The strain gages bonded to the coupling spacer are also subjected to these factors. Extreme applications may preclude the use of a strain gage based system, or limit the service life of the system.

Strain gage systems are generally considered a good option for short-term monitoring and test stand applications. Depending on the bandwidth of the electronics and the data acquisition rate, strain gages can detect higher frequency torsional vibrations such as those present in synchronous motor drives.

Phase shift type torquemeters are generally all metal construction without electronics embedded in the rotating coupling. As a result, they can handle more extreme environments and have a greater long term reliability. The variations between different phase-shift systems usually concern the construction of the rotating components and the design of the sensor system. There are several methods of locating and attaching the sensors to either an existing coupling guard or a guard specially manufactured by the torquemeter supplier.

Phase shift systems generally have an accuracy of less than 1% error full-scale torque for the life of the system. Strain gage systems have a comparable accuracy in the short-term, however this accuracy may degrade over the life of the system (2 – 5% error) due to such factors as thermal drift and hysteresis.

RECENT ADVANCEMENTS IN TORQUEMETERS

There have been several improvements in torquemeter technology in recent years. With tremendous increases in the speed of microprocessors, much of the signal conditioning and timing functions are now handled by digital technology rather than older analog circuitry. Newer systems have been developed that have moved the signal processing functions closer to the source of the signals, namely the sensors located in the hazardous area. Therefore, the distance the raw signal must be sent is greatly reduced. Previously, the raw signals would be transmitted to the control room for processing by the electronics. This limited the distance the signals could travel and required higher cost, low capacitance cable to minimize the susceptibility of the sensor signal to noise. Even then, there was still the possibility of noise corrupting the signal.

The processed torque, power, and speed data is sent from the conditioning unit to the control room through a digital serial communication link using industry standard communication protocols. Digital communication reduces the cost of long distance cross-site wiring, and also allows the data to be transmitted much further than raw sensor signals could. Using industry standard communication such as ModBUS RTU allows the user's data acquisition equipment to talk directly to the signal processing unit. Conversion of the data from digital to analog in the torquemeter electronics and analog back to digital again in the PLC equipment is eliminated. This allows all data to be transmitted by a single pair of wires rather than separate analog loops for each piece of data. In addition, diagnostic and error conditions can be transmitted across the serial link. The use of a serial communication and standard protocols also opens the door for wireless connectivity and communication over Ethernet networks.

CONCLUSIONS

1) Torquemeters are becoming a more important tool for turbomachinery predictive maintenance and performance evaluation.
2) Torquemeters are generally classified as either strain gage based or phase shift. Each type as its own advantages and disadvantages. Phase shift systems are known for greater long term reliability and accuracy, while strain gage systems can obtain torque data at higher data acquisition rates.
3) Incorporation of digital signal processing increases the reliability and accuracy of torquemeter systems, lowers the installed cost of the system, and allows for direct connectivity to the user's data acquisition system.

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