How to Select a Rotating Torque Sensor

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Why choosing the proper rotating torque sensor is important

There are two key reasons for taking the time to carefully select a torque sensor: to prevent damage and ensure accuracy.

Prevent damage - The torque sensor is a critical component of accurate measurement and, by design, can act similar to a mechanical fuse. Proper selection is important in order to avoid a mechanical failure as the torque sensor is one of the weaker parts of the driveline. This is because, to measure torque accurately, strain must be directed to an exact point and a strain gauge must be placed over that point - generally the weakest point of the sensor structure.

Ensure accuracy - It is important to limit the uncertainty of torque data. By ensuring that all of the electrical requirements of the torque sensor are addressed, you can acquire the best possible data, making it more usable in your specific application.

This white paper will help you choose the proper torque sensor for your needs by reviewing:

- **Types of torque sensors**, such as reaction, circular shaft, analog telemetry, digital telemetry and dual-range torque sensors
- **Application considerations**, such as accuracy, capacity range, RPM rating, output requirements and response times

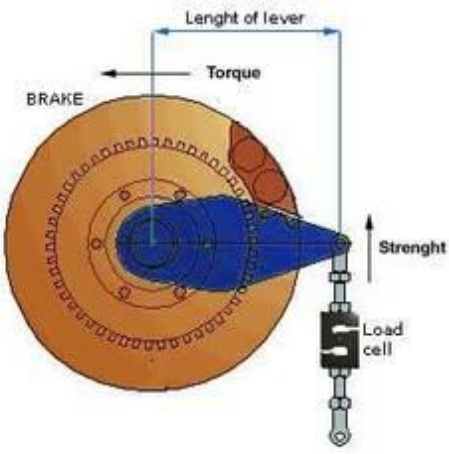
- **Environmental considerations**, such as temperature, dirt and electromagnetic interference
- **Dynamic considerations**, such as rotational effects, critical speeds and extraneous loading
- **Physical requirements**, such as size and mounting limitations of the torque sensor
- **Costs or budget** considerations

Types of torque sensors

There are many types of torque sensors. Understanding the pros and cons of each is the first step in selecting the right sensor for your application and needs.

Reaction torque sensors

Reaction torque sensors are non-rotating torque sensors, which act similar to a lever arm and a load cell, without actually needing either.



Advantages:

- **Cost effective**
- **Fewer considerations** - because the torque sensor isn't rotating, there are no RPM considerations.
- **No modifications to the rotating shaft** - You don't have to break the rotating shaft to install a rotating torque sensor and couplings, leading to less cost.

Disadvantages:

- **Reduced dynamic response time** - The mass of the dynamometer acts as a mechanical filter.
- **Not measuring true torque in the shaft** - Instead of measuring true torque in the shaft, you're measuring torque that is filtered by the mass of the dynamometer.
- **Bearing maintenance of the dynamometer** - The dynamometer floats on bearings in order to measure reaction torque.
- **Accuracy** - Because of the above, a reaction torque sensor is not as accurate as an in-line torque sensor.

Circular shaft - Slip ring-style torque sensor

A slip ring-style torque sensor was designed about 40 years ago. It uses graphite brushes that rub against silver alloy slip rings.

Advantages:

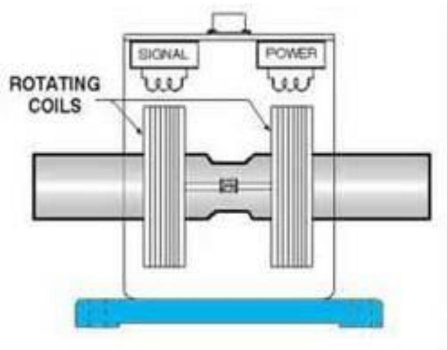
- **AC or DC excitation**
- **Higher response times** - It uses a contact method of measuring torque.
- **Low inertia** - Because of the circular, keyed shaft, there's usually a low inertia.
- **Low torque capacity ranges at a reasonable cost** - It can be made in low capacity ranges, down to 1 newton meter or below.
- **Mounting options** - This type of sensor allows you to foot-mount or not foot-mount the sensor, in case you have to move the critical speed of the driveline.

Disadvantages:

- **Stiffness**
- **RPM limitations** - Bearings, slip rings and brushes limit RPMs.
- **Bearing maintenance** - Bearings will fail over time and wear out, so they need to be replaced. Brush maintenance and errors - Graphite brushes create dust, and if the dust mixes with oil, the oil and dust can lay on the slip rings and cause electrical shorts.
- **Electrical brush noise**
- **Backlash or key imbalance** - The shafts are generally keyed, causing imbalances.

Circular shaft - rotary transformers

Rotary transformers are mechanically similar to the slip ring sensor. But electrically, it uses rotary transformers instead of using slip rings and brushes. One transformer is used to excite the torque sensor, and a second transformer is used to take the data back.



Advantages:

- **Non-contact data transmission** –These torque sensors can generally spin at a higher rate because they are non-contact and are not limited by the slip rings and brushes.
- **Low inertia** - Because of the circular, keyed shaft, there's usually a low inertia.
- **Low torque capacity ranges at a reasonable cost** – It can be made in low capacity ranges, down to 1 newton meter or below.
- **Mounting options –** This type of sensor allows you to foot-mount or not foot-mount the sensor in case you have to move the critical speed of the driveline.
- **Higher RPM ratings then slip rings**

Disadvantages:

- **Must use an AC excitation source**
- **Lower response times** – Around 300Hz of frequency response can be expected.
- **Stiffness**
- **RPM limitations** – Bearings limit RPMs.
- **Bearing maintenance and errors** - Bearings will fail over time and wear out, so they need to be replaced.
- **Electrical noise** – Transformers can act as an antenna
- **Backlash and key imbalance –** The shafts are generally keyed, causing imbalances.
- **Sensitive to vibration** – Vibration and misalignment, or a thrust force, can easily damage the transformer parts.

Circular shaft - clamp-on style torque sensors

Clamp-on style torque sensors are ideal when it’s not feasible to break the shaft and install in an in-line torque sensor.

Advantages:

- **Low cost for high torque ranges** - If you have a shaft that's a foot in diameter, it's a lot easier and more cost effective to clamp on a torque sensor versus install an in-line torque sensor.
- **Low torque capacity ranges**
- **Higher RPM ratings**

Disadvantages:

- **Low accuracy or high uncertainty** - It doesn't measure torque but rather deflection in the shaft.
- **Difficult to repeat** - You have to know how the shaft is manufactured and what the properties are of the shaft to repeat the test results.
- **Requires mathematical calculations** - You need to convert the shaft deflection to a torque.

This torque sensor is more for convenience and not for applications where accuracy is a critical requirement.

Analog telemetry torque sensor

In the early 1990s, analog telemetry became reasonably cost effective and accurate.

Advantages:

- **Non-contact data transmission** - No bearings allow for a 24/7 maintenance free solution.
- **Stiffness** - Flange to flange rotor design allows for high stiffness.
- **Low or virtually no backlash** - No keways or splined shaft ends.
- **High RPM ratings**
- **Low electrical noise** - It's less susceptible to noise because of the frequency output.
- **Weight and length** - Telemetry sensors are generally lighter and shorter than slip ring or rotary transformer-style torque sensors.

Disadvantages:

- **Inertia** - Because they're larger in diameter, the inertia is higher.

- **Susceptible to nearby metal objects** - A guard or a shield can act as a secondary antenna and draw power or the signal away from the torque sensor, making it non-functional.
- **Better but limited response times** - These torque sensors have higher response times than a rotary transformer type torque sensor.

Digital telemetry torque sensor

Over the last five to ten years, digital telemetry became a more feasible way of making torque sensors. They are more high-tech than other sensors and have more advantages versus other torque sensors in the marketplace.

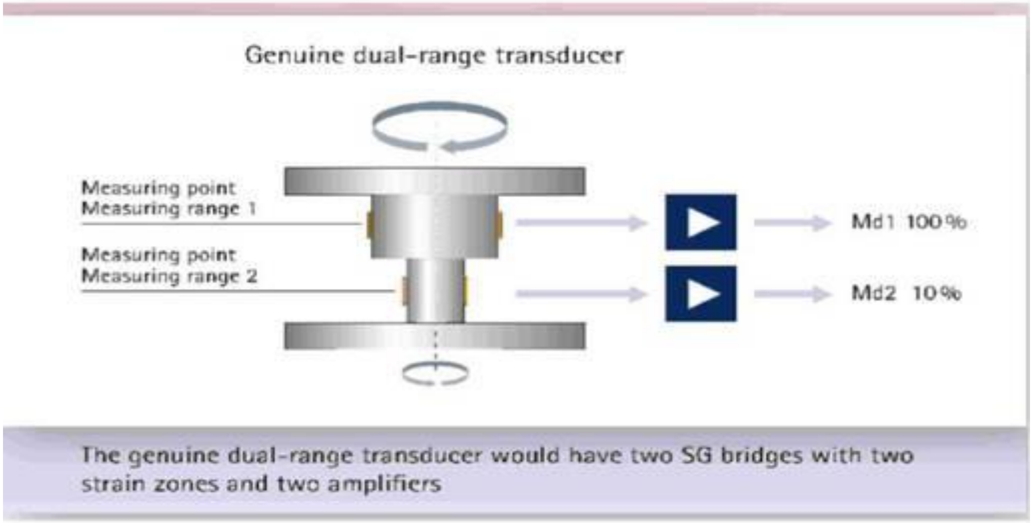
Advantages:

- **Lower uncertainty** - Because it’s digital and because there’s software involved, it has a lower uncertainty.
- **Non-contact data transmission** - It runs in a 24/7, no-maintenance environment.
- **Stiffness** - Flange to flange rotor design allows for high stiffness.
- **Low or virtually no backlash** - No keways or splined shaft ends.
- **High RPM ratings.**
- **Low electrical noise** - It’s less susceptible to noise because of the frequency output.
- **Weight and length** - Telemetry sensors are generally lighter and shorter than slip ring- and rotary transformer-style torque sensors.
- **Set up software available.**
- **May not be susceptible to nearby metal objects.**
- **High response times** - It can have anywhere from 1 kilohertz up to a 10 or 15 kilohertz of response time.

Disadvantages:

- **Inertia** - Because they're larger in diameter, the inertia is higher.
- **Cost** - Especially in lower capacity ranges.
- **Data conversions** - There will likely be more conversions, depending on the output type. For example, it may convert from analog across the bridge to digital transmission and then back to an analog signal output.

Dual-range torque sensor



There are some vendors that offer dual-range torque sensors. HBM's point of view is that these sensors are practically impossible to manufacture. In order to have a true dual-range torque sensor, it would have to have, for example, one 10,000 Newton meter bridge and one 1,000 newton meter bridge. If both of these bridges existed on the same torque sensor, once you put 10,000 Newton meters on it, you would twist and destroy the smaller bridge.

It's virtually impossible to mechanically overload-protect a torque sensor in order to protect the smaller capacity bridge. So, typically one or two 10,000 newton meter bridges are used offering a separate calibration for the 1,000 newton meter range. Typically, there is also a voltage gain added to increase the output from the smaller strain gauge bridge. Filtering is then applied to clean up the noise, which can have an adverse effect on accuracy and measuring at the low end.

Ultimately it's not highly possible to manufacture a true dual-range torque sensor. However, you can use some digital torque sensors with software and configure them to act as a dual-range torque sensor.

Application considerations

A torque sensor's datasheet is a useful resource for comparing sensors for your specific application. Datasheets can indicate how a torque sensor will generally perform. However, all of the values on the datasheet are recorded in a lab environment, so most of the data is static, not dynamic or rotating. You'll need to consider how the torque sensors will perform when spinning in your application.

Accuracy (non-linearity) requirements

Measurement accuracy, or level of uncertainty, is a key consideration when selecting a torque sensor because different applications require different levels of uncertainty. For example:

- Efficiency testing, friction loss testing and drag torque demand low uncertainty, requiring a torque sensor such as an HBM T12
- Endurance testing, end-of-production test and horsepower verification need moderate uncertainty levels, requiring a torque sensor such as an HBM T40B
- Assembly equipment testing, torque-to-turn applications or fastener testing can at times handle a higher level of uncertainty, requiring a torque sensor such as an HBM T20 or HBM T22

How do you quantify the measurement uncertainty of a torque sensor? While it can be complicated, a sensor's uncertainty generally has six components:

- Sensor output and sensitivity
- Linearity and hysteresis
- Temperature effect at zero
- Temperature effect at full scale
- Repeatability
- Off-axis loading (usually axial, lateral and bending movements)

You can use a measurement uncertainty formula (see image 10) to estimate an uncertainty number using data from a torque sensor's data sheet.

Factored into a sensor's uncertainty is its calibration data. So, it's important to know what type of calibration equipment your vendor uses and how uncertain is the calibration equipment. In some countries, torque is not always a completely controlled measurement, so the vendor becomes responsible for assuring you, the customer, of the accuracy of its lab. One can weigh the weights, measure the arm, and calibrate the instrumentation, but in some areas of the world there is no controlling entity to ensure that the procedures are consistent among vendors—or even that the equipment is working properly.

In some countries, there are governing organizations that control torque measurement. In Germany, the PTB (similar to the National Institute of Standards and Technology) verifies the accuracy of the lab calibration equipment and issues a certification. By choosing a vendor with this type of certification, you can be more confident in the data on a torque sensor's calibration datasheet.

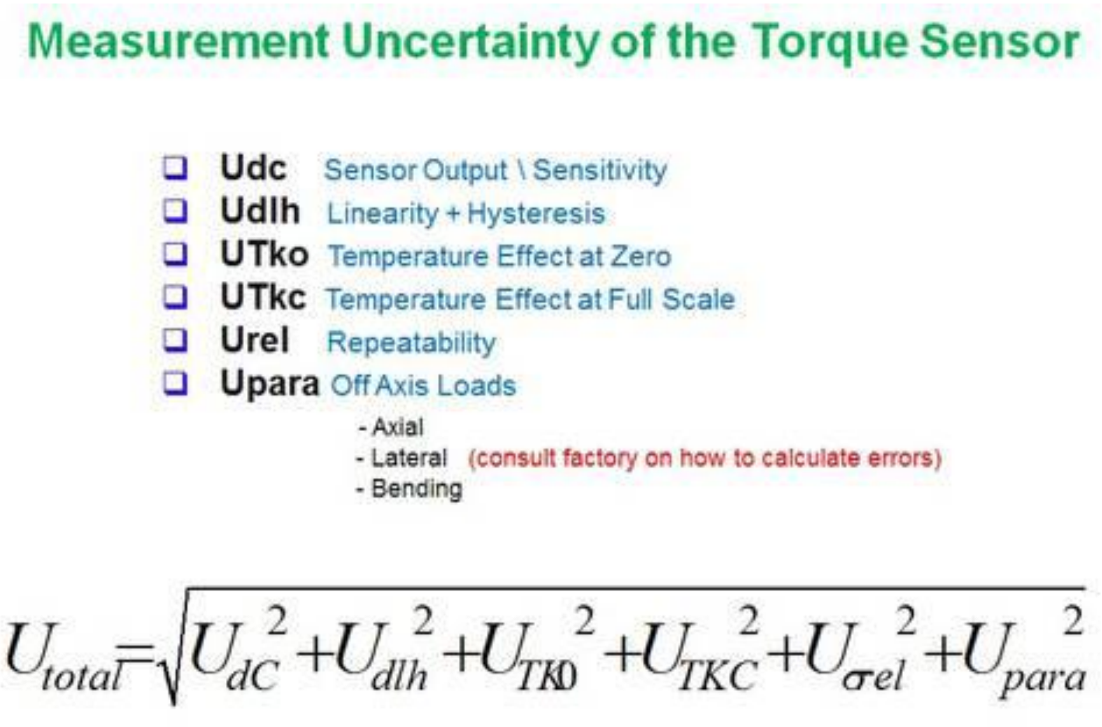


Image 10: Measurement uncertainty formula

Capacity range

When considering torque sensors, it’s important to accommodate all of the peak torques and spikes. These spikes, if outside the safe range of use, can damage a torque sensor. And if the time periods of these spikes are short enough and the response time of the torque sensor is low enough, you may not even see them in your data until the damage is done. So, it’s important to know your torque range and choose a torque sensor that can accommodate these spikes.

Moreover, you must decide whether you want to measure these torque spikes or just survive them. If you want to measure the spikes, you have to make sure that your sensor’s electrical outputs can measure the spikes that you want to read.

However, if you're only concerned with measuring the working (average) torque, electrical filtering or using torsionally soft members in the driveline can remove or dampen the spikes. This can allow you to size the torque sensor closer to the working torque.

Overload ratings

It’s also important to know the overload ratings of a torque sensor. Typically, the industry standard for safe sensor overload is around 200 percent of full scale - the point at which the sensor will start to yield. It would take many overloads at this rating for the torque sensor to start failing, usually seen in a zero shift. Catastrophic overload typically can occur around 400 percent of full scale - the point at which bolts may fatigue or the sensor may fail by cracking or bending.

If you prefer a more generous overload rating, some vendors offer a 400 percent safe overload and an 800 percent catastrophic overload. However, raising the overload rating increases the stiffness of the torque sensor and decreases the resolution, or signal-to-noise ratio, at the low end. It also typically means that the sensor is larger and heavier by design to accommodate stronger forces. You need to decide whether to sacrifice a higher overload rating for size, weight and signal-to-noise ratio.

Rotations-per-minute (RPM) rating

Most torque sensors in the marketplace are rated between 10,000 and 20,000 RPMs. Weight, balance and critical speed are factors to consider when choosing a sensor's RPM rating.

Weight - Typically, when you go up in capacity range, the torque sensor must spin more slowly - mostly due to its weight and diameter. There are some torque sensors rated to higher RPMs, such as the HBM T11, which is rated to 30,000 RPMs. This sensor is made of titanium to cut down on the weight.

Balance - Some torque sensors are balanced at the factory before being shipped. If a torque sensor is pre-balanced, it's typically to a G 2.5 balancing rating. Check with the sensor's manufacturer to find out if it will arrive balanced.

Critical speed - The critical speed is the RPM at which the driveline wants to become unstable. Usually the torque sensor will be the first thing to fail in this type of a situation. To help avoid a critical speed, you can choose a torque sensor with bearings and a foot mount. This will shorten the unsupported shaft as the torque sensor will act as a bearing block.

Output requirements

Your torque sensor's output will typically go to some sort of instrumentation, such as a strain gauge conditioner or data acquisition (DAQ) system. On reaction torque sensors - or older-model, slip-ring-type torque sensors - the outputs are usually millivolt per volt, which is a strain gauge output. When using such an output, typically an AC or DC strain gauge conditioner is used to power the sensor and then condition the output to a usable signal, usually analog or digital. Plus or minus 10 volts DC amplitude signals are often more susceptible to noise than a frequency or digital output.

Frequency outputs are a time base signal and are less susceptible to noise than amplitude outputs. So more-modern torque sensors also give a frequency output:

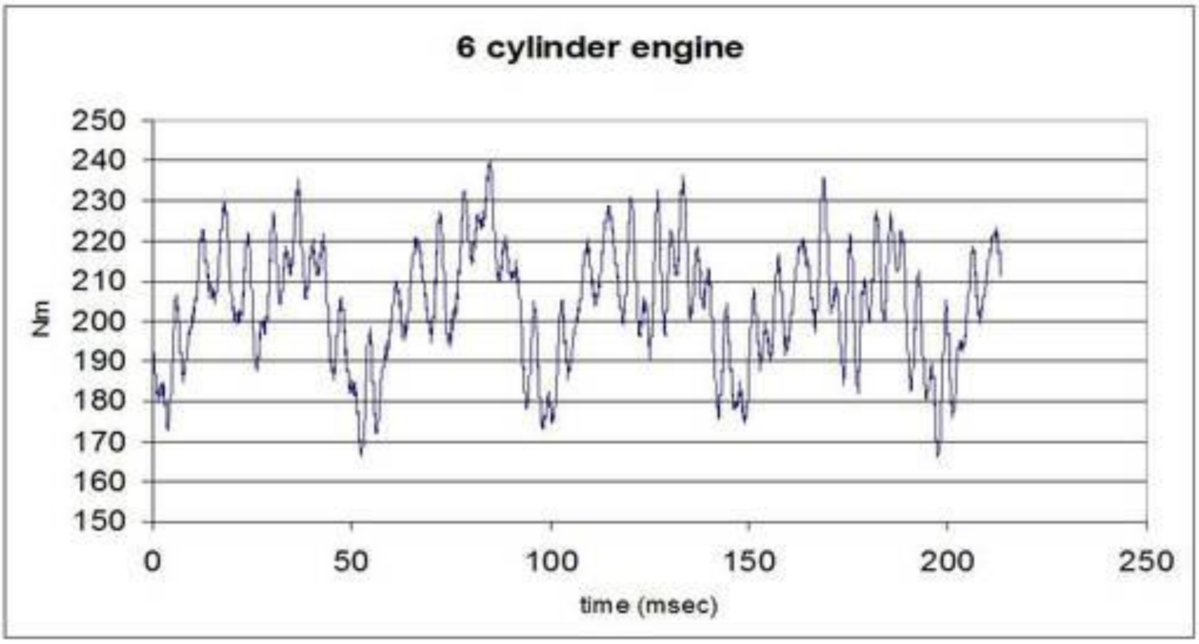
- 10 kilohertz +/-5 kilohertz
- 60 kilohertz +/-30 kilohertz
- 240 kilohertz +/-120 kilohertz

The lower the frequency, the better the resolution. In other words, a 10 kilohertz output will typically have more resolution than a 240 kilohertz output. This is because raising the frequency usually generates more noise down at the low end. However, the advantage of a higher-frequency output is that it can increase the response time and lower the propagation delay - the time it takes for a torque event to happen on the input and then be seen on the output of the torque sensor.

It's good to note that digital torque sensors can come with outputs such as CAN, ProfiBus, ProfiNet and EtherCAT. Because of fewer signal conversions, the overall performance can improve. If a torque sensor isn't equipped with digital outputs, you can usually purchase a separate device to achieve digital communication.

Response times

When evaluating torque sensors, it's important to consider your application's response-time requirements as well as the ratio between the sampling rate and response time to avoid aliasing. Some torque sensors have a 3:1, 6:1 or even a 12:1 ratio, such as the HBM T12. These high response times will allow you to measure torsional vibrations.



Environmental conditions

Environmental conditions such as temperature, dirt, oil, corrosion and EMI should affect your choice in a torque sensor.

Temperature

Like all strain-gauge-based sensors, torque sensors are sensitive to temperature, so it's important to know whether you are dealing with a gradient or air soak temperature change in your environment.

A gradient change affects one side of the torque sensor first, when making its way down the metal shaft. Effectively, one side of the torque sensor can be warmer than the other side, possibly causing the sensor to twist. An air soak is a more uniform temperature change, similar to placing the sensor in an oven. An air soak temperature change is compensated for by the manufacturer and is listed on the sensor's data sheet.

A torque sensor's manufacturer can often supply information on how the sensor performs while under temperature changes. Usually, torque sensors are put in ovens with the temperature dialed up and down to gather data on how well the torque sensor performs under a changing-temperature environment.

It's important to note that the more strain gauges a sensor uses in its construction, the better it can perform during temperature changes - as long as they're laid on the metal sensor properly. Also, if a steel sensor is manufactured properly, the effects of temperature change are minimized.

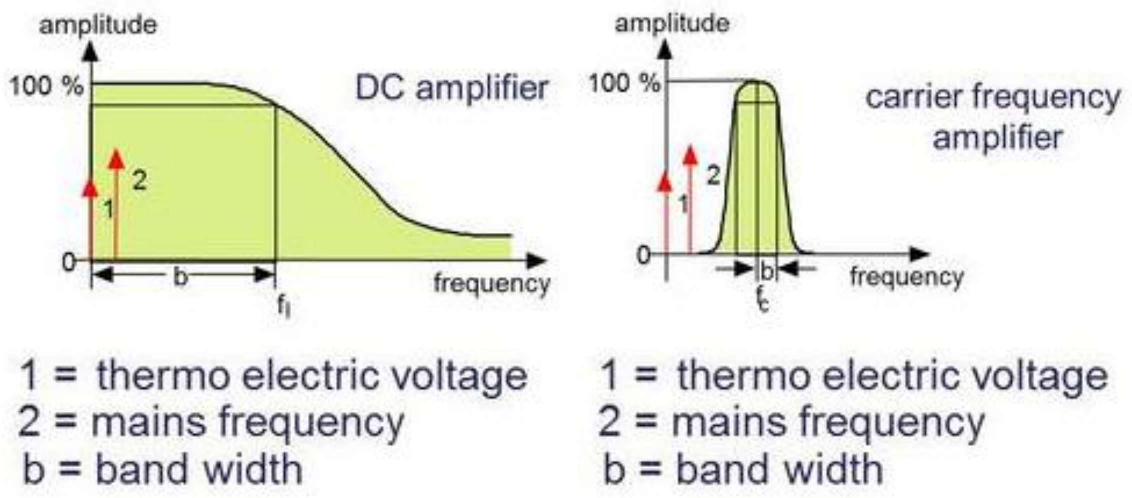
Dirt, oil and corrosion

Consider a torque sensor's construction in terms of protection against dirt, oil and corrosion - particularly the more sensitive parts. Also, some sensors are more hermetically sealed than others, which is important in a harsh environment.

You also need to know how the torque sensor data is transferred and whether the transfer method is susceptible to oils and dirt. For example, in slip-ring sensors, dirt and oil are more likely to affect the signal transmission back to the stationary world. These sensors are more susceptible to oil and dirt than digital telemetry systems.

Electromagnetic impulses (EMIs)

Torque sensors are basically antennas - they have wires and coils inside, so proper cabling, shielding and grounding is critical. Find out what kind of signal conditioning is being used on the torque sensor. Is it AC or DC excitation across the Wheatstone bridge? At HBM, we generally recommend AC strain gauge conditioning because it's more noise-immune than DC strain gauge conditioning. It minimizes the errors that DC can cause due to thermal or 1F noise sources.



Dynamic considerations

Modern torque sensors are designed to be torsionally stiff with higher frequency response times. This gives the end user a greater capability to measure dynamic torque.

Image 14 illustrates a diesel-engine torque measured on a dynamometer that has an in-line torque sensor as well as a lever arm and load cell. If the frequency of the oscillating torque is higher than the natural frequency of the dynamometer, then the lever arm configuration can act as a mechanical low-pass filter, generally around 20Hz.

In this signature, the lever arm load cell (in blue) gives a filtered, average torque signal; whereas, the in-line torque sensor (in red) gives you a more dynamic torque signal - this is the advantage of the rotating torque sensor: its measurement, or the signal, is more dynamic.

When a shaft starts to spin, a number of effects can occur that will influence the torque sensor and its ability to read torque correctly. Dynamic considerations should include rotational effects, critical speeds and extraneous loads.

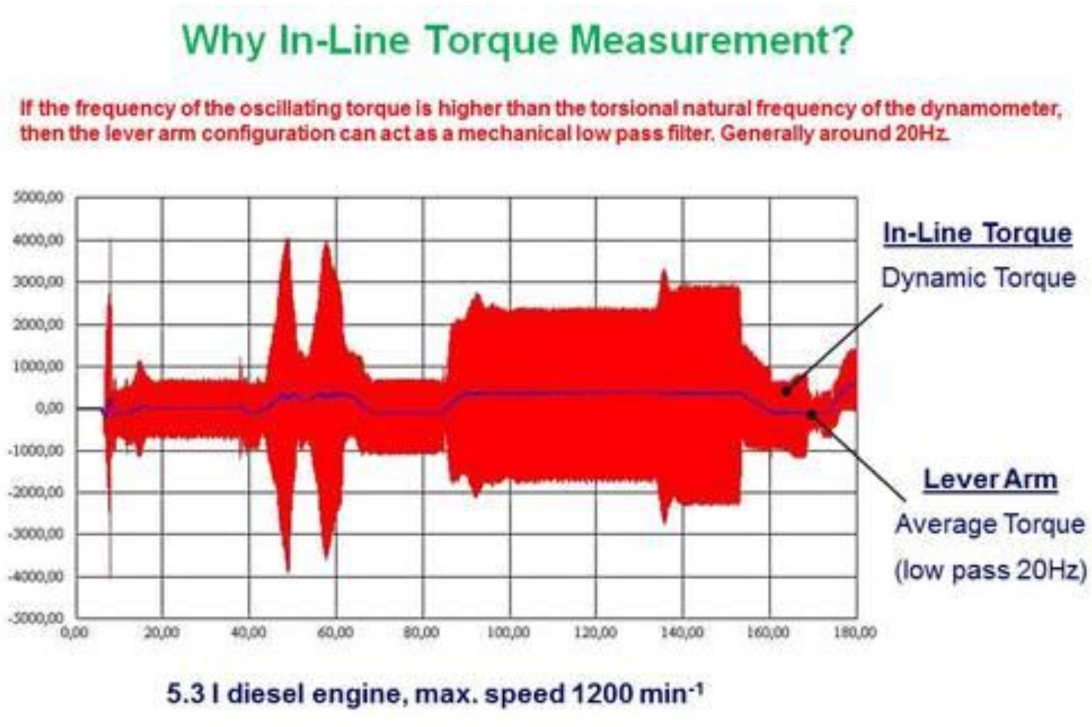


Image 14: A diesel-engine torque measured on a dynamometer

Rotational effects

Rotational effects can influence the torque sensors output. One type of rotational effect is windage - or the effect on the torque sensor just spinning in air. Another type includes the actual forces on the spinning sensor - like how spinning affects the strain gauges, wires and electronics. At higher RPMs, the effect on the torque sensor becomes greater. These effects should be small but can be seen on a torque sensors output signal.

Unfortunately rotational effects aren't listed on most datasheets. This is because the rotational effects vary depending upon RPM and can change from application to application, making it difficult to quantify. However, some companies do compensate for rotational effects. It’s important to ask the vendor about the rotational effects of its torque sensor and how they are mitigated.

Critical speeds

To help eliminate critical speeds of a rotating shaft, a perfect torque sensor would weigh nothing, have infinite stiffness and have no length at all. While this is of course impossible, a vendor should aim to manufacture a torque sensor as stiff as possible, as light as possible and as short as possible.

At a specific RPM, the shaft will want to become unstable, and when critical, the shaft will act as a sine wave or vibrate. Once the shaft becomes unstable, the torque sensor is susceptible to mechanical failure, such as cracking into two pieces. So, it's always good to do a torsional analysis of your rotating shaft before using the test stand.

HBM recommends making your test stand as simple as possible. The fewer the parts, the fewer opportunities there are for error.

Once you choose the right torque sensor for your needs, learn more about installing it in HBM's "21 Tips on How to Install a Torque Sensor" white paper.

It's a good idea to keep most of the torque sensors' weight as close to a bearing block as possible in the test stand. In image 15, the torque sensor and the coupling are close to the dynamometer - in this case, an electric motor - on the left. By keeping the majority of the weight close to a bearing block, you can move your critical speed outside of the measurement range and help to prevent a catastrophic situation.

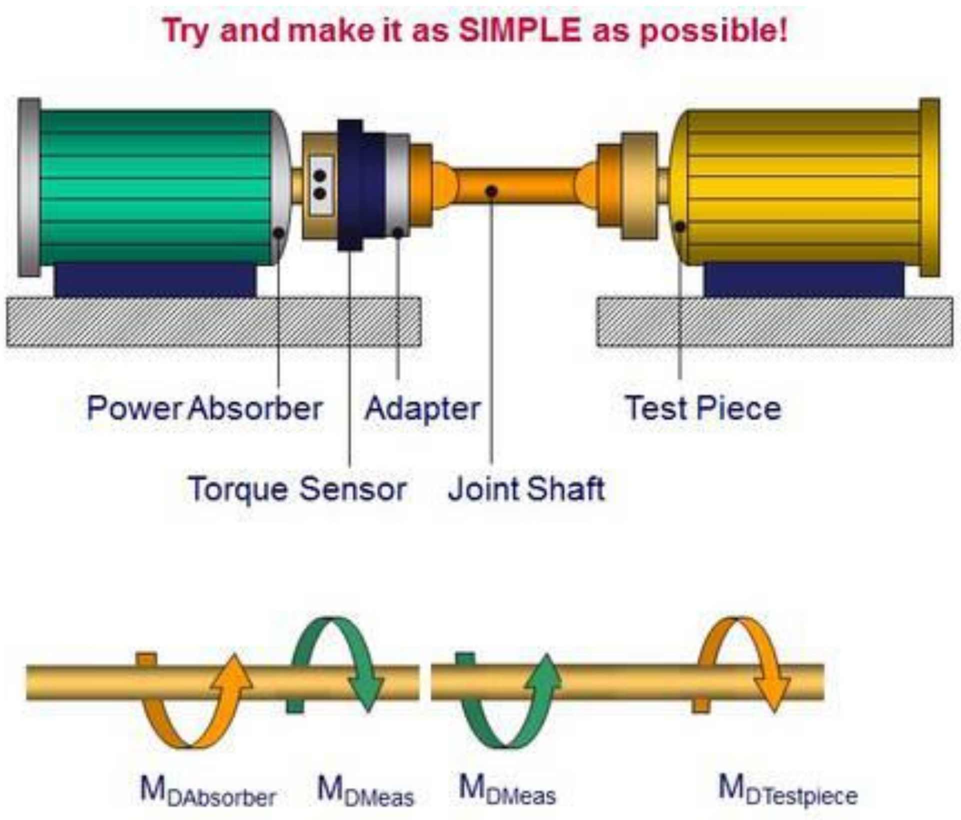
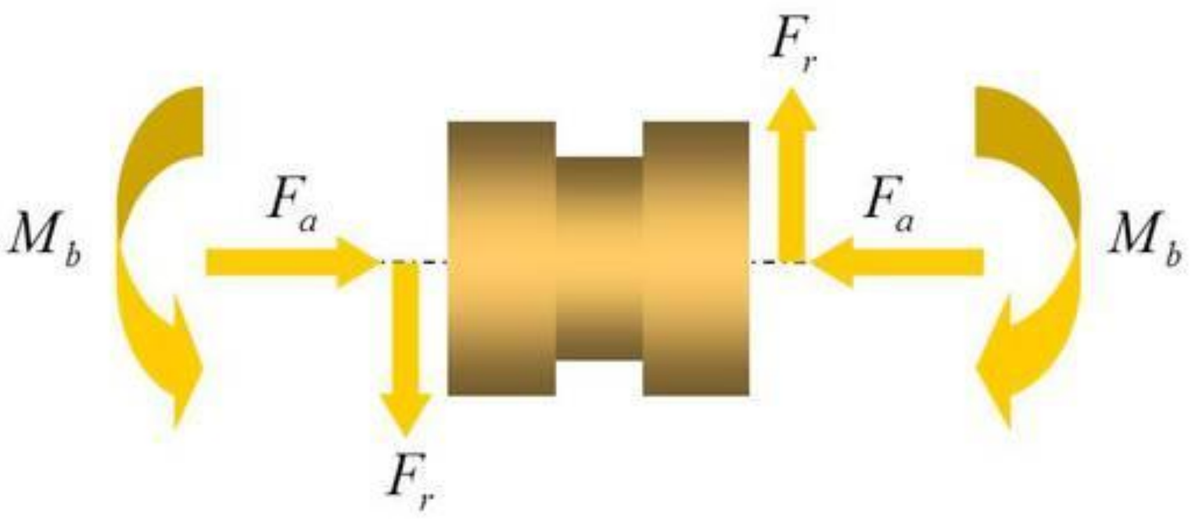


Image 15: A torque sensor and coupling are close to a bearing block

Parasitic loading

Parasitic loads are axial forces, lateral limit forces and bending moment forces that occur when the shaft is spinning. These off axis forces can add a very large error to a rotating torque sensor, just like temperature changes. Eliminating these forces will help you increase the accuracy, or lower the uncertainty, of your test stand.

The supplier of the torque sensor can help you to understand these parasitic forces, how they affect the torque sensor, and how much error you can expect when these forces are applied to the torque sensor. Most manufacturers give parasitic forces limits on their datasheets. While these limits generally aren't catastrophic, the maximum of these limits can start to affect the output of the torque sensor. Typically, if you reach 100 percent of the combined parasitic force limits, you can expect a .3 percent of full-scale error on your torque sensor. So, minimizing the parasitic loading in the application is important.



Physical requirements

When choosing a torque sensor, you must know the physical limitations of the application, primarily so you can accommodate the length and weight of the sensor. Flange-to-flange torque sensors are often shorter, lighter and more rigid. Circular-shaft torque sensors are typically longer and heavier and practically always less rigid.

You must also contend with space requirements. Flange-to-flange sensors are typically larger in diameter. Circular, keyed shafts are typically smaller in diameter and allow you to pedestal-mount or foot-mount the sensor. In other words, a circular torque sensor can become a bearing block and change the critical speed of the driveline—for better or worse.

The torque sensor mounting configuration determines what type of couplings you should use. Flange-to-flange torque sensors are typically floating torque sensors. They're not foot-mounted and usually require one dual-flex type coupling. Circular, keyed shaft torque sensors with no foot mount also require one dual-flex coupling. Once a foot mount is used, two dual-flex type couplings are required. Your vendor can help you with the proper coupling method for the particular type of torque sensor that you select.

Cost or budget considerations

Rotating torque sensors typically start at around $2,000 in price. Usually, square drive-type torque sensors with slip rings are the least expensive. Typically, torque sensors above 10,000 newton meters are the most expensive.

The cost of a torque sensor increases with:

- A higher capacity range
- Better accuracy (less uncertainty)
- A higher RPM rating

- Non-contact
- More outputs
- Custom configurations
- Software

While cost is almost always a factor in business purchases, it should be the last consideration, after all of your other needs are met. Valuing cost over other needs may lead to inaccurate testing or a damaged sensor.

About the Author

Mark Minda is the business development manager for HBM's torque products. He has more than 20 years of experience in the repair, calibration and day-to-day use of torque sensors. Mark has been with HBM for seven and a half years.

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