SIEMENS

Siemens PLM Software

Identifying best practices for measuring and analyzing torsional vibration

White Paper

This white paper explains what torsional vibrations are and how they can be measured. It gives an overview of the different instrumentation methods for measuring torsional vibration, including advantages and disadvantages, allowing you to select the best instrumentation method for your needs. It also reveals best practices for conducting instrumentation and analysis.

www.siemens.com/plm/lms

A white paper issued by: Siemens PLM Software.

Contents

Executive summary..3

Torsional vibration analysis 4
What are torsional vibrations? 4
Where do torsional vibrations occur? 4

Torsional quantities 5
Angular position, velocity and acceleration 5
- Angular position or angular displacement 5
- Angular velocity 5
- Angular acceleration 5

Torque 5
- Torsional stress/shear-stress method 5
- Twist-angle method 5

Twist angle and twist RPM..5
Transmission error 6

Measurement sensors for torsional vibration 7
Direct measurements...7
- Linear accelerometers 7
- Angular accelerometers 7
- Strain gauges 7
- Dual-beam laser interferometers 8

Coder-based techniques...9
- Magnetic pickups 9
- Missing pulse correction 10
- Optical sensors...10
- Zebra tapes 10
- Incremental encoders 11

Pulse-signal conditioning 12
- Analog tacho 12
- Digital tacho – TTL..12
- Digital tacho: differential TTL 12

RPM and angle-reconstruction methods...........................13
Number of pulses per rotation..13
- Nyquist-Shannon sampling theorem 13
- Response bandwidth of mechanical systems.................13
- Relation-order bandwidth for rotating machinery 13
- Optimal number of pulses per rotation 14

Processing and analysis 15
Torsional resonances and torsional orders 15
- Torsional orders 15
- Torsional resonances 15

Tools for advanced processing 15
- Fourier analysis 15
- Angle-domain analysis...15
- Torsional animation 16

Annex 1..17
Tips and tricks for proper installation of zebra tape 17

Annex 2..18
Pulse detection techniques 18
Digital tacho (counter)...18
Analog tacho...18
Tacho reconstruction algorithm 18

Executive summary

With the advent of ecological engineering comes a new range of issues to solve. New powertrain designs – such as start-stop systems, downsized engines, advanced torque lockup strategies and lighter powertrains – emphasize the importance of developing an in-depth understanding of torsional vibrations as they can diminish comfort as well as engine and driveline efficiency. That is a concern in the case of power transmission systems using rotating shafts and couplings, and is therefore important to turbo-machinery manufacturers and integrators as well as makers of marine drivelines.

This white paper provides an overview of the instrumentation and challenges of torsional vibration testing, and gives practical guidelines so you can efficiently quantify and qualify torsional vibrations and its root causes.

Torsional vibration analysis

What are torsional vibrations?

Torsional vibrations are angular vibrations of an object, typically a shaft along its axis of rotation. As mainly rotational speeds are measured, torsional vibrations are assessed as the variation of rotational speed within a rotation cycle. These revolutions-per-minute (RPM) variations are typically induced by a rough driving torque or a varying load. Structurally-sensitive frequencies along a driveline may amplify and transfer these phenomena, leading to comfort, durability or efficiency problems. The level of torsional vibration is influenced by a number of parameters, such as material properties, operating conditions (such as temperature, load, RPM, etc.) and need to be taken into account.

Despite tremendous progress in modeling accuracy, overall-system complexity still necessitates accurate qualification and quantification of these torsional vibrations under controlled or real-life operating conditions in order to better understand and refine counter measures.

Where do torsional vibrations occur?

Torsional vibrations are of importance whenever power needs to be transmitted using a rotating shaft or couplings, such as in the case of automotive, truck and bus drivelines, recreation vehicles, marine drivelines or power-generation turbines. The figure below provides an overview of the different components that can generate torsional vibrations in ground-vehicle drivelines. Similar figures can be created for marine drivelines or power transmissions in the turbo-machinery industry.

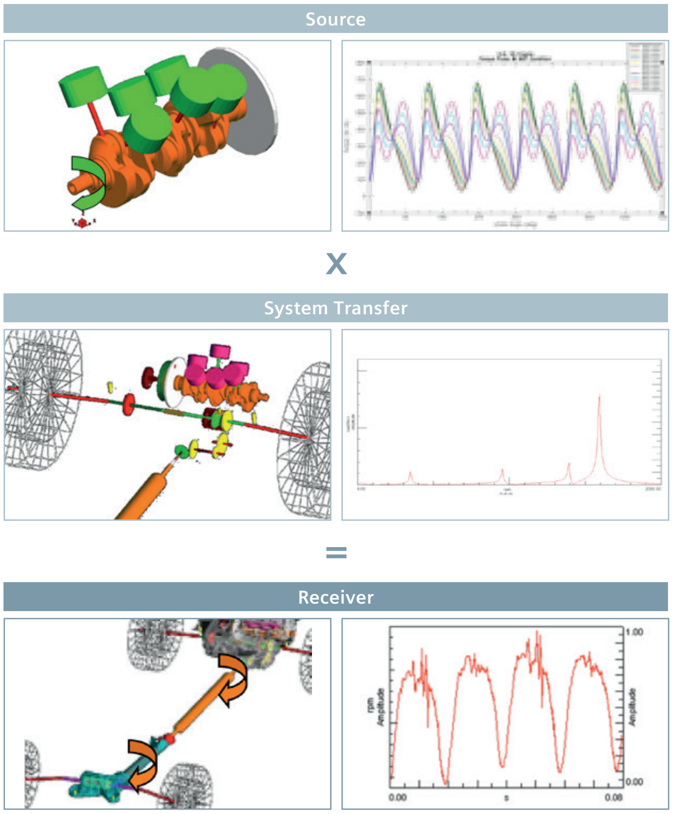


Figure 1. Root-causes analysis linking torsional and structural responses to the torsional sources.

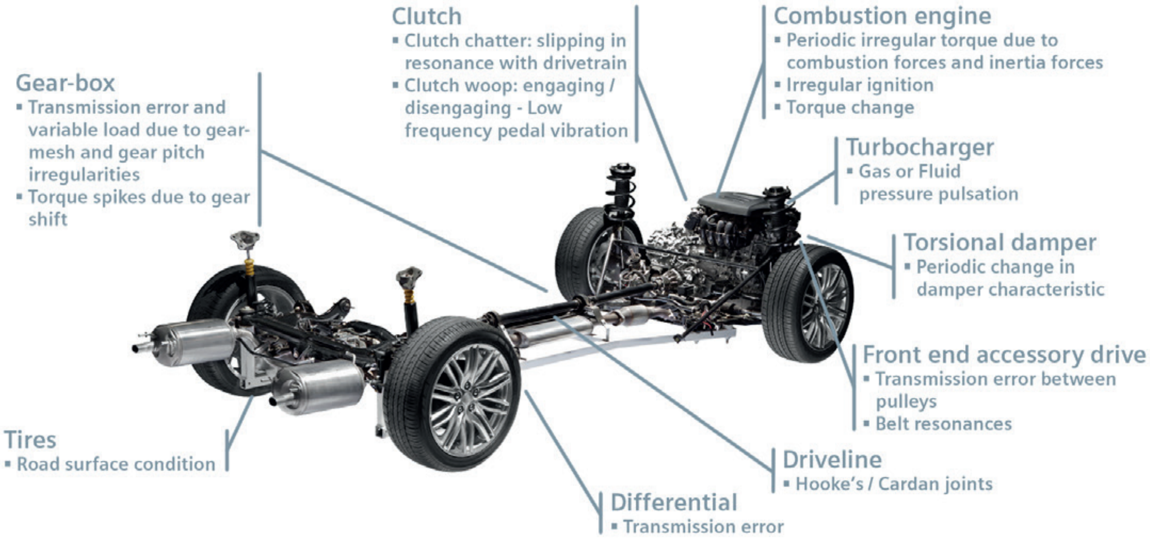


Figure 2. Torsional vibration-related issues.

Torsional quantities

Angular position, velocity and acceleration

Angular position or angular displacement

$\alpha(t)$ in [rad] or [°]

Angular velocity

$\frac{d\alpha(t)}{dt}$ in [rad/s] or [°/s] or [RPM]

Angular acceleration

$\frac{d^2\alpha(t)}{dt^2}$ in [rad/s2] or [°/s2]

All three quantities are directly linked to each other, and can be derived by integration and differentiation. The choice of measurement quantity depends mainly on the type of sensors used. The most common quantity used to measure torsional vibrations is the angular velocity or RPM.

Torque

Torque quantifies the source of excitation. The angular velocity and displacement as discussed before quantifies the response of the applied torque. Torque and angular velocity are linked to each other. The basic formulation of a shaft in free conditions is:

$$T = \frac{d^2\alpha}{dt^2} J_z$$

With
T [Nm] is the torque,
Jz [m4] is the torsion constant or the polar moment of inertia

This formulation is similar to the formulation of Newton's law, which links the force acting on a mass to the acceleration of that mass.

Different techniques exist to measure the torque. Two methods based on the shear-stress measurement and the twist-angle measurement are described here:

Torsional stress/shear-stress method

Most torque sensors are based on the measured shear stress at the outer surface of the shaft, which can be converted into torque by means of:

$$T = \frac{\tau J_z}{R}$$

Where
T [Nm] is the torque,
τ is the maximum shear stress at the outer surface (torsional stress),
Jz [m4] is the torsion constant or the polar moment of inertia,
R [m] is the outer section of the shaft.

For a circular section of the shaft,

R is the radius of the shaft and

$$J_z = \frac{\pi \cdot R^4}{2}$$

Twist-angle method

The easiest instrumentation is based on the measurement of the relative-angle deformation between two separate locations on the shaft.

$$T = \frac{GJ_z \Delta\alpha}{L}$$

Where
T [Nm] is the torque,
GJz is the torsional stiffness (G [GPa] is the shear modulus, Jz [m4] is the torsion constant or the polar moment of inertia),
Δα [rad] is the angle of twist, or twist angle
L [m] is the length of the shaft.

For homogeneous isotropic materials, the shear modulus can be derived from the Young's modulus and the Poisson's ratio.

$$G = \frac{E}{2(1+\nu)}$$

Where
E [GPa] is the Young's modulus,
v is Poisson's ratio

Twist angle and twist RPM

The twist RPM is the difference in RPM between the two extremities of a shaft. This difference in RPM between the two locations, the so-called twist, is a measure for torsional vibration on the shaft.

$\text{Twist angle} = \text{angle}_{position2} - \text{angle}_{position1}$

$\text{Twist rpm} = \text{rpm}_{position2} - \text{rpm}_{position1}$

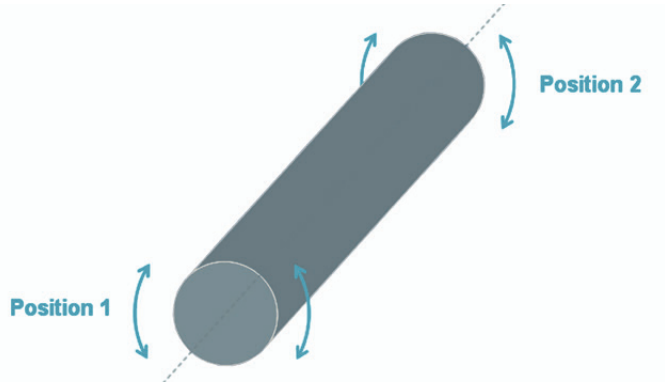


Figure 3. Shaft torsion is estimated by measuring angular position or velocity on both extremities of the shaft.

Transmission error

In mechanical transmissions in which rotating energy is transmitted from one rotating shaft to another, such as gearboxes or belt interconnected shafts, transmission errors may occur.

The transmission error is the difference between the measured and theoretical angular position and the velocity of the output shaft. It can be expressed as an absolute or relative value and can be expressed in relation to the driving or the driven shaft.

In other words, the transmission error quantifies the difference between the actual power transmission and the ideal power transmission. As such, it quantifies the imperfection of the device in transmitting its power, or quantifies the dynamics that are added or lost by the transmitting device to the input power.

Classical reasons for having a transmission error would be gear eccentricity, gear-tooth bending, gear teeth not being constant in thickness, belt resonances, etc.

Different mathematical or physical formulations of the transmission error are:

$$Te = rpm_2 - Tr \cdot rpm_1 \quad \text{or} \quad Te = rpm_1 - rpm_2/Tr \quad \text{or}$$

$$Te = \frac{\alpha_1 - \alpha_2/Tr}{\alpha_1} \quad \text{or} \quad Te = \alpha_1 - \alpha_2/Tr \quad \text{or}$$

$$Te = \frac{\alpha_2 - Tr \cdot \alpha_1}{\alpha_2} \quad \text{or} \quad Te = \alpha_2 - Tr \cdot \alpha_1$$

Where
Te is the transmission error, α1 and α2 are respectively the angle measured on input and output shaft, rpm1 and rpm2 are respectively the angular velocity measured on input and output shaft, Tr is the transmission (gear) ratio.

A value of 0 for transmission error would indicate a perfect transmission.

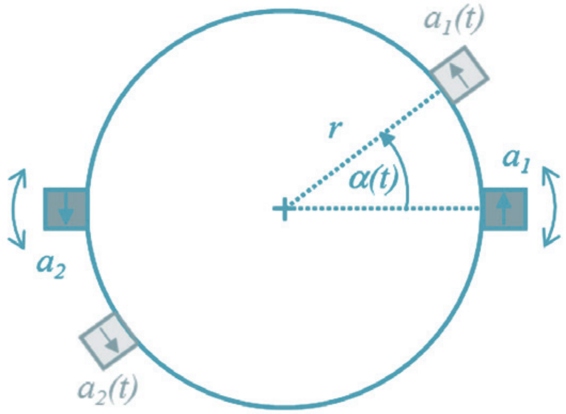
Measurement sensors for torsional vibration

Various measurement techniques are available for torsional vibration. The best sensor can be selected for each individual case based on the quantity to be measured, the type of analysis, the accessibility of the shaft, the ease of instrumentation and the required accuracy or level of detail.

Direct measurements

Linear accelerometers

Two linear accelerometers are fixed in parallel on the rotating shaft as shown in figure 1. The two accelerometers will measure the tangential acceleration. As they move in the opposite direction in the fixed system of the rotation axis, any translational acceleration of the shaft is cancelled by taking the average of both accelerometers. The angular displacement, velocity and acceleration can be computed according to equations from figure 4.



$$r.\alpha = \iint \frac{a_1 + a_2}{2} dt^2$$

$$\Rightarrow \alpha = \iint \frac{a_1 + a_2}{2r} dt^2$$

$$\Rightarrow \dot{\alpha} = \omega = \int \frac{a_1 + a_2}{2r} dt$$

$$\Rightarrow \ddot{\alpha} = \frac{a_1 + a_2}{2r}$$

Figure 4. Linear accelerometers configuration.

To conduct vibration and harshness (NVH) analysis, we prefer the RPM quantity.

$$RPM = \frac{60}{2\pi} \int \frac{a_1 + a_2}{2r} dt$$

Advantages:

- High-dynamic range directly determined by the used accelerometers
- Low sensitivity to the shaft-translational vibrations when the two accelerometers are properly aligned

Disadvantages:

- Expensive telemetry system or sensitive slip rings are needed to transfer the acceleration signals from the rotating shaft to the measurement hardware
- Mass loading for relatively small shafts influencing the structural behavior of the shaft, e.g. causing torsional resonances to shift in frequency or shaft unbalance
- Bigger shafts at relatively high RPM cause centrifugal force that may lead to dangerous loss of accelerometers and measurement equipment when not sufficiently glued
- Since acceleration is measured, and angle and speed can only be derived by integration, no absolute angular position is available. For example, angle domain processing will not be possible

Angular accelerometers

Sensor manufacturers propose fully-integrated angular accelerometers to be fixed on shaft extremities, including the sensors and the slip ring. Some are based on linear accelerometers applying the method described in the previous paragraph. Other techniques like torsional springs can also be used.

Strain gauges

Strain gauges are glued on the shaft to measure the torsional elongation or stress (shear stress). As the stress is directly measured, this method is often used in durability tests to estimate the torsional fatigue.

Torsional vibration is mostly measured in half-bridge configurations, with two strain gauges positioned at a 45-degree angle on the shaft. For a full-bridge configuration, four strain gauges are placed (two on the shaft's front side and two are on the shaft's back side). The symmetric configuration compensates for unwanted measured quantities such as bending stress (figure 5).

Advantages:

- Direct measurement of the torsional elongation of shear stress
- Low sensitivities to other deformation than torsional

Disadvantages:

- Expensive telemetry system or sensitive slip rings are needed to transfer the acceleration signals from the rotating shaft to the measurement hardware. These systems may influence the structural behavior of the shaft due to mass loading
- Bigger shafts at relatively high RPM cause centrifugal force that may lead to dangerous loss of accelerometers and measurement equipment when not sufficiently glued
- Exact angular speed and position are not known. Since acceleration is measured, and angle and speed can only be derived by integration, no absolute position is available. For example, angle- domain processing will not be possible

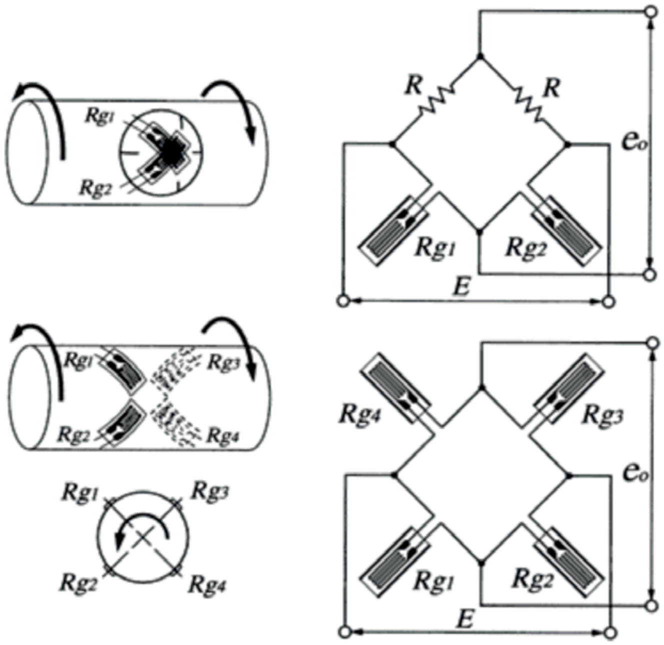
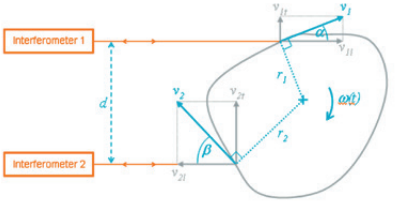


Figure 5. Half bridge and full bridge configuration applied to torsional measurement.

Dual-beam laser interferometers

Laser interferometers can be used as well to measure torsional vibration. Laser manufacturers typically proposed specific systems for rotating measurement based on dual-beam techniques to cancel the effect of translational movement of the shaft.

The angular velocity is computed from the velocity measured in the direction of the laser beams on the two pointed areas. Figure 6 illustrates the technique principle.



$$f_1 = f_0 - \frac{v_{1l}}{\lambda_0},\ f_2 = f_0 + \frac{v_{2l}}{\lambda_0}$$

$$v_{1l} = v_1 \cos(\alpha) = \omega . r_1 \cos(\alpha)$$

$$v_{2l} = v_2 \cos(\beta) = \omega . r_2 \cos(\beta)$$

$$\Delta f = f_2 - f_1 = \frac{v_{2l}}{\lambda_0} + \frac{v_{1l}}{\lambda_0} = \frac{\omega . d}{\lambda_0}$$

$$\Rightarrow \omega = \frac{\Delta f . \lambda_0}{d}$$

Figure 6. Torsional laser principle based on Doppler Effect.

Advantages:

- Contactless measurement
- Low sensitivity to shaft-translation vibration
- Low sensitivity to the shape of the shaft
- Easy instrumentation

Disadvantages:

- Expensive device. Since it is frequently required to measure torsional vibrations at different shaft locations simultaneously, this is often a very large drawback
- Exact angular speed and position are not known. Since velocity is measured, the angle can only be derived by integration, so no absolute position is available. For example, angle- domain processing will not be possible
- The size of the device does not allow using it in a confined environment. Its use in real-life mobile conditions is very difficult or nearly impossible

Figure 7. Torsional laser setup.

Coder-based techniques

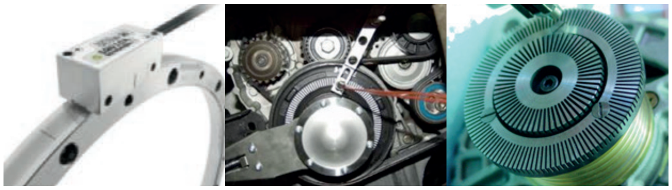
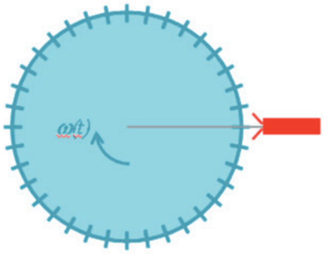


Figure 8. Examples of coder-based setup.

Coder-based techniques make use of equidistantly-spaced markers on the shaft or rotating part. The sensor measures every time a marker passes in front of a sensor and the time difference between two markers is used to estimate the angular velocity.



$$\alpha_i = \alpha_{i-1} + \Delta\alpha$$

$$\Delta\alpha = \frac{2\pi}{ppr} = \frac{360°}{ppr}$$

$$rpm_i = \frac{60}{(t_i - t_{i-1}) \cdot ppr}$$

Figure 9. Coder-based measurement principle.

The coder-based techniques have the advantage of delivering RPM and discrete angle position. The data resolution is determined by a number of markers: the more markers, the more accurate information, although for low speeds, you need more markers than for high speeds.

Different types of setups are used to provide markers (coder); for example, stripes drawn on the shaft or the teeth of the gears. Also, different sensors are available to detect the markers, such as electro-magnetic pickup or optical sensors. Incremental encoders are devices combining the coder and the sensor in a single hardware.

Magnetic pickups

Magnetic pickups can be used to detect changes in the magnetic field or magnetic flux, typically resulting from metallic teeth passing the sensor. They are often used in industrial applications because they are robust and have low sensitivity to ambient dust. Setups for this are often very practical as well, since existing gear sets on the machine can be used as coder, e.g. gear-teeth on flywheels of transmissions. As a result, magnetic pickups are very popular for measuring torsional vibration because they are easy to set up, they work very well with existing gear teeth and are very robust. Most combustion engines today are equipped with them so they can transfer the different shaft positions to the engine or gearbox controllers.

Passive sensors, such as the magneto-resistive or the magneto-inductive, are the most popular and cost effective. The measured voltage from the sensor is generated by the changing flux provided by Faraday's law:

$$V = -N.\frac{d\Phi}{dt}$$

With
V generated magnetic voltage
N number of wires in coil of the sensor
Φ magnetic flux

As the change of the magnetic flux comes from the rotation of the shaft, the sensor does not need to be powered. The amplitude and the shape of the delivered signal varies with the speed of the shaft (as this affects the differential of the magnetic flux) and may affect the accuracy of the teeth detection, mostly at low rotational speeds.

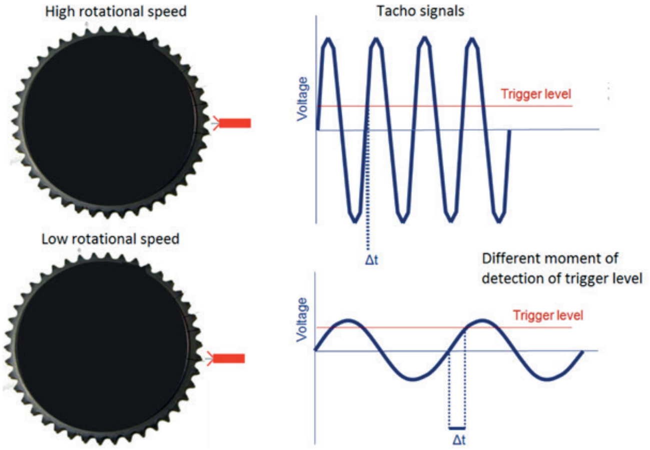


Figure 10. Influence of the rotational speed on the pulse level.

Other magnetic sensors are based on the Hall effect. Often those sensors are equipped with a miniaturized-electronic circuit to condition the output to deliver a standardized digital signal (TTL) type of output signal. They will also need to be powered.

Advantages:

- Price: mass production of magnetic pickup for automotive or industrial application has a very positive influence on their end-user price
- Simplicity of instrumentation: the sensor is typically fixed on non-rotating components, which removes the need, e.g. telemetry. Coders are mostly generated by existing gear sets

Disadvantages:

- The number of teeth on the gear set limits the number of pulses per rotation, which could be insufficient to capture all torsional content

- Accuracy of the measurement will be dependent on the machining accuracy and deformation of the gear teeth
- The sensor must be fixed very closely to the rotating shaft (less than 0.5 centimeters), which is sometimes difficult, for instance when the shaft has an important translational movement
- Relative displacement between the magnetic pickup and the shaft due to shaft bending, or due to displacement of the sensor attached on a mounting that is too soft, will influence the quality of the measured pulses and generate a fictive torsional vibration

Missing pulse correction

Coder wheels sometimes come with one or two consecutive missing teeth to generate an absolute angular reference position per rotation. Engine manufacturers use this possibility to synchronize the equipment linked to the coder with the cylinders' top death center (TDC).

However, when such a setup is used to provide coder pulses for torsional vibration analysis, missing pulse correction algorithms are needed. If not, the missing coder pulse would generate a spike in the RPM or angle estimation

Although it's clear that such coder will never be as accurate for torsional vibration measurements as the ones without missing pulses, they are often used when doing measurements on engines because they can provide the TDC reference and are present in most engines.

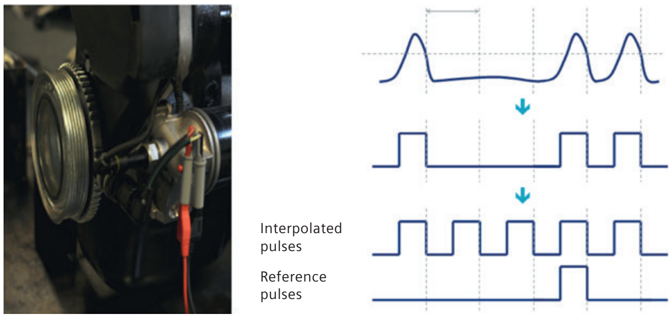


Figure 11. Missing pulses correction algorithm. An interpolation method is used to re-generate the missing pulse. The next pulse directly after the missing one is used as absolute angle reference.

This configuration requires special care for the magnetic pickup sensor. The hysteresis of the sensor does not always allow a good and accurate detection of the pulse located directly after the missing one.

Optical sensors

Many types of optical sensors can be found on the market, but most of them are designed for object detection. To measure torsional vibrations, the sensor not only needs to be able to detect a high rate of events per second, but the timing accuracy of that detection is also very important and the accuracy is often insufficient.

Optical sensors generate an electric signal proportional to the received versus light intensity. Optical fibers are used to conduct the light from the emitter to the sensor head, and back from the sensor head to the receptor. They can be configured in reflection or transmission configuration.

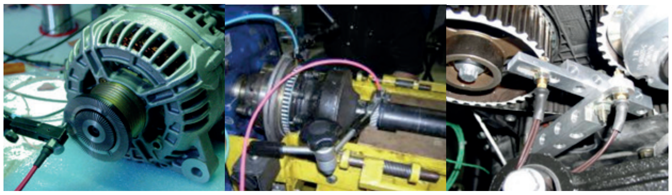


Figure 12. Examples of optical sensor setups.

Optical sensors can be used with much different type of coders as soon as the visible contrast between the stripes can be sufficient. Most optical sensors deliver TTL output signal.

Advantages:

- The instrumentation can be extremely simple as the sensor is typically fixed on non-rotating components. Only the coder needs to rotate
- Optical sensors can be directly instrumented on gears as we would do with magnetic pickups under condition that the reflection of the material gear surface is sufficient
- Coders can easily be implemented on the shaft with contrasted paint or zebra tapes
- Quick response and phase accuracy of good quality optical sensor allows the measurement of a very high pulse rate

Disadvantages:

- The sensitivity to ambient light and/or the quality of the material reflection complicates the direct instrumentation of the gears in gearboxes
- The sensor must be fixed very closely to the rotating shaft (less than 0.5 centimeters), which is sometimes difficult when the access is limited or when the shaft has some important translational movement
- Relative displacement between the magnetic pickup and the shaft due to shaft bending or displacement of the sensor, attached on a mounting that is too soft, will influence the quality of the measured pulses and generate a fictive-torsional vibration

Zebra tapes

Black and white tapes are increasingly used to quickly implement a coder on a shaft. It can be used to create a coder where no gear wheel is available or when a higher number of pulses per rotation are needed. There are two families of tape depending if it must be glued around the shaft (zebra tape) or on the extremity (zebra disc). Zebra tapes and discs exist in multiple-stripe width to adapt to the number of pulses per revolution in the functioning of the shaft diameter.

Although zebra tape is very easy to instrument, an error will be introduced onto the measurement at the location where two zebra tape endings come together. When this point passes the optical sensor it will introduce a discontinuity in the RPM signal. The automatic-correction method detailed in the paper 'Zebra Tape Butt Joint Algorithm for Torsional Vibrations' must be applied before analysis of the measured signal. Guidelines to obtain optimal results with zebra tape are developed in annexes.

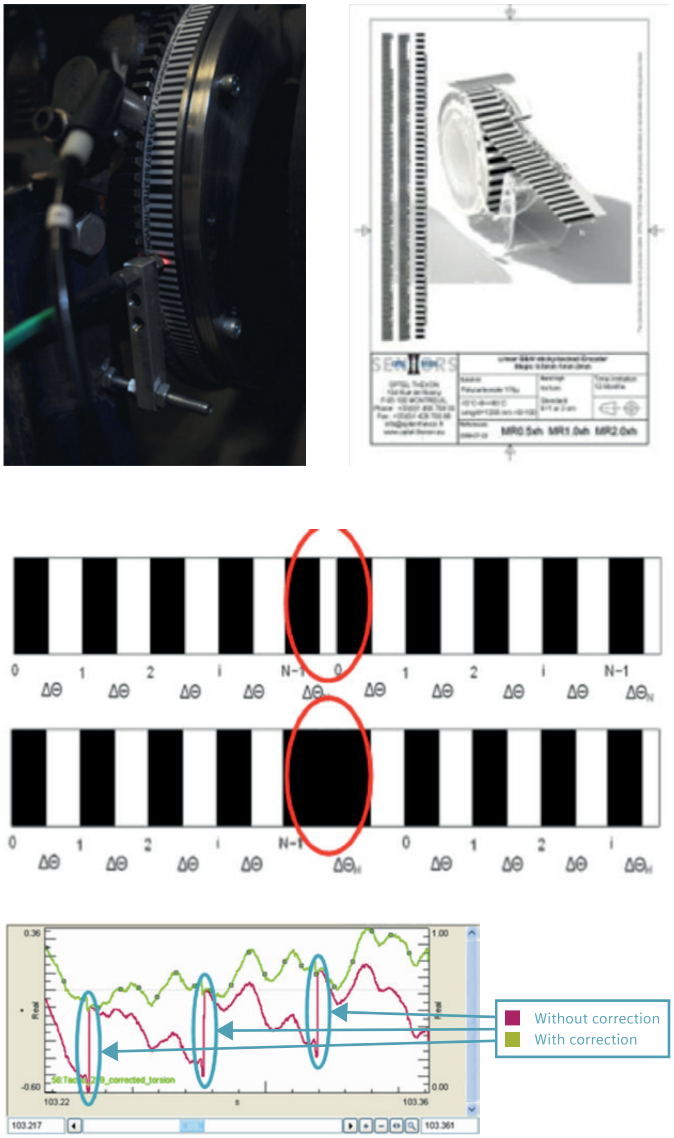


Figure 13. Zebra tape instrumentation and LMS automatic correction.

Zebra discs do not suffer from the inherent butt joint issue, but proper care needs to be taken to properly center the disc. Since perfect centering is never possible, harmonic or order 1 is typically not reliable when using this coder setup.

Incremental encoders

Incremental encoders are devices typically used in automat or robotic applications for accurate detection of shaft positions. The high accuracy of incremental encoders makes them very attractive for torsional- vibration analysis applications as well. Often based on optical technology, incremental encoders combine the coder and the sensor in a single device. This means in practice that it consists of both a rotating (rotor) and a static (stator) component and the full sensor needs to be mounted on the setup. Incremental encoders come in many different shapes and sizes to cover all required applications.

Figure 14. Zebra tape instrumentation and LMS automatic correction.

The incremental encoder makes use of three embedded coders: one detecting a single pulse/revolution, called an index, as an absolute angle reference, and two more high-resolution encoders called A and B. The A and B signals have the exact same number of pulses, but the B signal is phase-shifted with a quarter of a pulse cycle (90 degrees) compared to A. Combining these two coder signals allows detection of the sense of rotation of the coder.

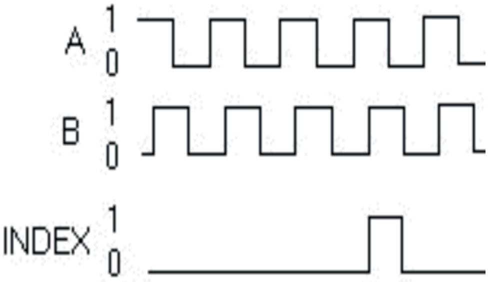


Figure 15. A, B and index signals from an incremental encoder.

Advantages:

- The fully-integrated approach allows you to develop accurate coders with potentially a very high-pulse rate. Incremental encoders can be delivered with the appropriate number of pulses, depending on the application and desired accuracy (typically 50 to 500)
- The sense of rotation can be a great advantage i.e. for the investigation of start/stop behavior on engines
- The integrated index signal by definition allows duty-cycle related analysis with accurate TDC identification (e.g. engine combustion analysis)

Disadvantages:

- The relatively complex instrumentation limits usage for in-vehicle or mobile measurements. Incremental encoders are mainly used when working on test benches in which the instrumentation is used to make part of the test-bench equipment

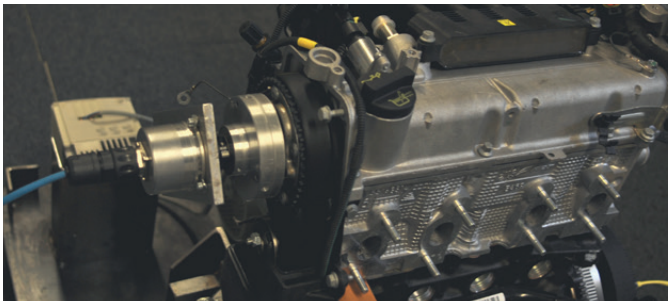


Figure 16. Incremental encoder instrumentation.

Pulse-signal conditioning

Magnetic pickups, optical sensors and incremental encoders all output periodic signals to be processed into angular velocity and/or position by acquisition hardware. Some sensors have dedicated circuits to preprocess or precondition the signal into a standardized type of output signal such as TTL or RS422/485.

The torsional-vibration measurement system must accurately detect the time stamps and named tacho moments at which a predefined level is crossed by the periodic-sensor signal assuming a fixed angle increment between pulses. The required hardware-signal conditioning depends of the type of sensor being used and its corresponding signal type.

Analog tacho

The output signal is delivered as measured by the sensor, which means in practice that it can have any shape. A user-defined trigger level is used to identify the tacho moments.

Digital tacho – TTL

Most optical sensors and some magnetic pickups are equipped with a dedicated level-detection circuit delivering a standardized digital signal, which allows clear and accurate detection of the tacho moments at higher pulse rates than the classical analog tacho.

Digital tacho: differential TTL

Single-ended signals are more sensitive to electrical noise than differential signals, especially when longer cable lengths are needed. That is why the differential standards RS422/485 are recommended for incremental encoders, in which the distance between the emitter and the sensor head cannot be changed.

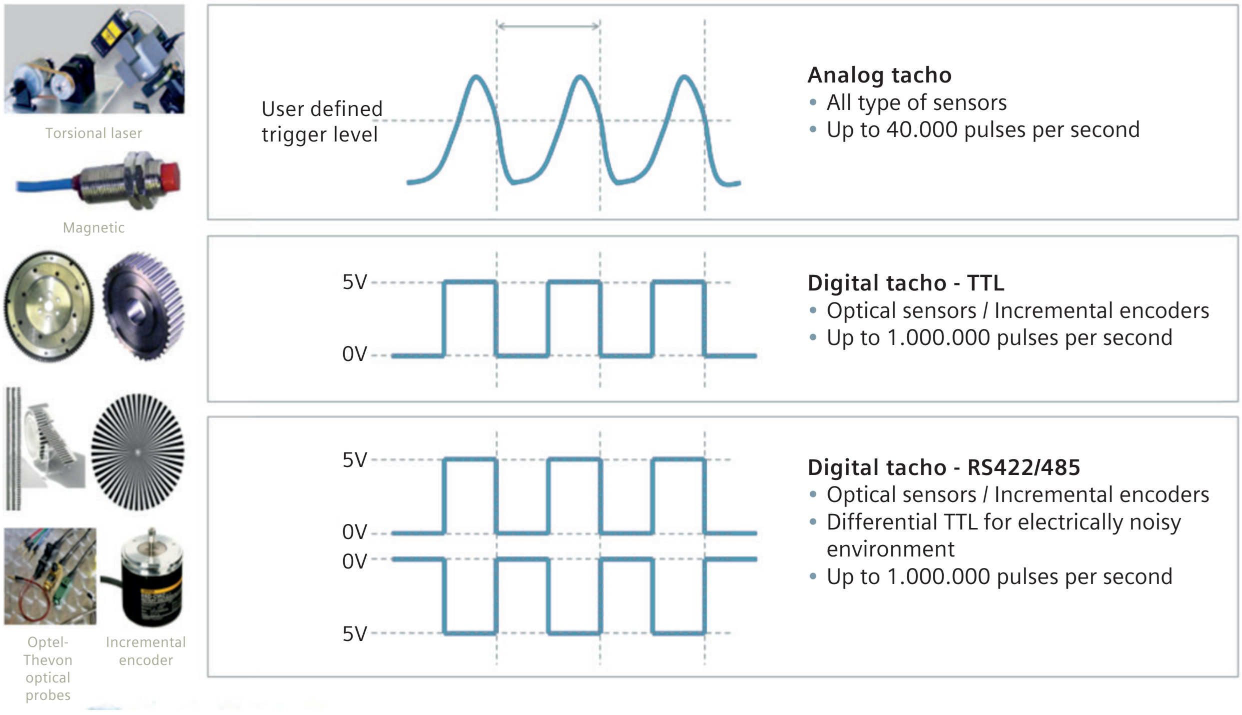
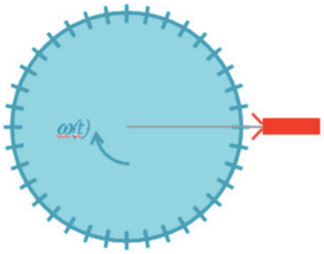


Figure 17. Pulse signal conditioning.

RPM and angle-reconstruction methods

When using coder-based sensors, each pulse detection moment corresponds to a known increase in angular position, i.e. at each tacho moment the angular position is known with respect to the first tacho moment.



$$\alpha_i = \alpha_{i-1} + \Delta\alpha$$

$$\Delta\alpha = \frac{2\pi}{ppr} = \frac{360°}{ppr}$$

$$rpm_i = \frac{60}{(t_i - t_{i-1}) \cdot ppr}$$

Figure 18. Each pulse corresponds to a known increase in angular position. The difference in time between two pulses can be used to estimate the rotational speed.

To process the data in time or in a frequency domain, interpolation techniques must be used to estimate the position or the speed between two detected tacho moments, and to generate a time-equidistant RPM or angle trace at the desired sampling frequency.

The interpolation method used can have an important impact on the quality of the analysis. Best-practice techniques include using digital reconstruction filters to avoid aliasing.

Figure 19 shows the difference in results when looking at an RPM color map with (on the left) and without (on the right) appropriate digital-reconstruction filters. Frequencies above 500 hertz (Hz) are aliased to lower frequencies and affect the order cuts.

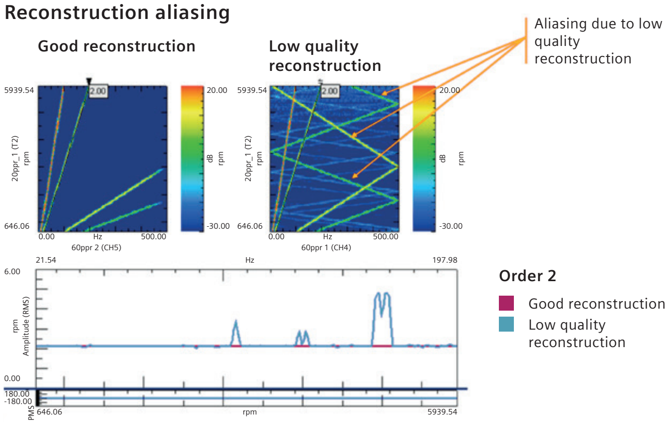


Figure 19. RPM reconstruction with (left) and without (right) digital reconstruction filter.

Number of pulses per rotation

The quality of coder-based torsional measurements is heavily impacted by a correct selection of a minimum number of pulses per rotation. In case too few markers per revolution are available, this will add an error, known as angle-domain aliasing, to the measured data. The minimum-coder resolution can be identified by using the three following principles summarized in the picture below.

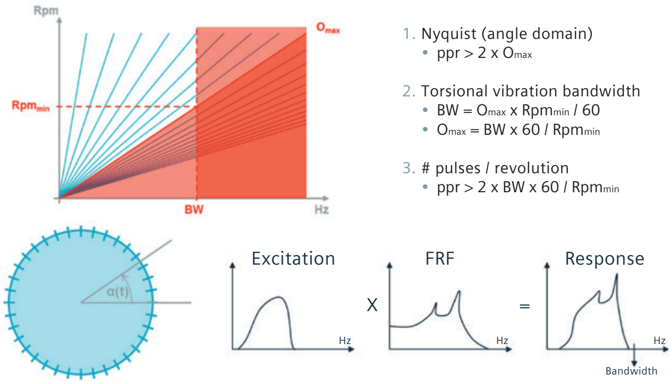


Figure 20. Number of pulses per revolution.

Nyquist-Shannon sampling theorem

In principal, the number of pulses per revolution required is determined by the Nyquist theorem applied to an angle domain acquisition:

If an angular function x(α) contains no order higher than O_{max}, it is completely determined by giving its ordinates at a series of points spaced $2\pi/(2O_{max})$ radians apart.

In other words, the number of pulses per rotation must be at least two times higher than the maximum order.

$ppr > 2\ O_{max}$

Response bandwidth of mechanical systems

Mechanical system responses to a certain excitation are limited in band frequency. The relevant-frequency range for torsional vibrations is limited to a maximum and this maximum depends on the structural dynamics of the mechanical system (the shaft or component being analyzed). It also means that once a specific overall RPM order exceeds the bandwidth, this order is no longer of interest.

Relation-order bandwidth for rotating machinery

The maximum order observed is a function of the bandwidth of the system and the rotational speed. For varying speeds (runups, rundowns, etc.), the minimum RPM determines this maximum-observed order.

$O_{max} = Bandwidth\ .\ 60\ /\ Rpm_{min}$

Optimal number of pulses per rotation

Based on those three principals, the optimal coder resolution can be estimated as follow:

$$ppr = 2 . O_{max} = 120 . Bandwidth / Rpm_{min}$$

As the bandwidth of the system cannot always easily be estimated, a safety factor of 2 or 4 is often applied.

In many cases, test engineers do not have the luxury of selecting the optimal coder for the test. When using coders available as part of the structure, such as teeth in gearboxes, it's always important to estimate the error made with too few pulses. The reversed equation 16 can be used to estimate the bandwidth of the coder for specific RPM conditions.

$$Bandwidth = ppr . Rpm_{min} / 120$$

Figure 21 illustrates the risk of angle-domain aliasing.

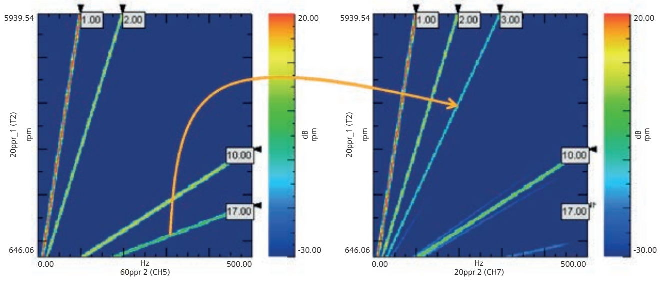


Figure 21. Angle domain aliasing. The same torsional vibration is measured with a 60 pulses per revolution (PPR) coder (left display) and a 20 PPR coder (right display). Orders 1 and 2 are perfectly measured with both coders. With the 20 PPR coder order 17 could not have been measured as expressed by the Nyquist-Shannon theorem and even more dramatically this order is aliased to order 3.

Processing and analysis

Once the measurements are done properly, specific-processing techniques are used to quantify the torsional-vibration phenomena or to correlate them with other acoustic or vibration responses of the structure.

Torsional resonances and torsional orders

As with other translational vibration analysis, we can distinguish the torsional orders from the torsional resonances.

Torsional orders

Torsional orders are forced responses induced by the cyclic excitation of the rotating source. A Fourier analysis of this irregular torque/RPM at a certain moment will show the different harmonics and the relative importance at that moment, thus related to the operating condition at that moment. The waterfall or color map of a combustion engine provides a global overview of the torsional-frequency behavior, and the dominant-torsional orders.

Torsional resonances

Torsional resonances, which are related to the structural properties of the system under investigation, are independent of the operating condition. When excited, they very often amplify the torsional vibration phenomena, so it is important to identify and quantify them.

As torsional excitation under operating conditions is mainly limited to the harmonics of the forcing torque, torsional resonance levels can be small compared to the orders. A good measurement-dynamic range will be important to avoid the torsional resonances being masked by the orders. Often the twist angle or the twist RPM is analyzed, since they remove most of the torsional orders and more clearly highlight the torsional resonances.

Accurate assessment of torsional resonances and torsional damping can be done via experimental modal analysis, often using a torsional-excitation signal, and measuring the torsional frequency-response functions (FRFs) between the torsional excitation and multiple rotational response degrees of freedom (DOF).

Tools for advanced processing

Fourier analysis

Stationary or tracked Fourier analysis helps to identify torsional orders and torsional resonances. Correlation analysis between torsional quantities and other response signals like vibration or acoustic response is possible as the exact same processing can be applied to both types of signal.

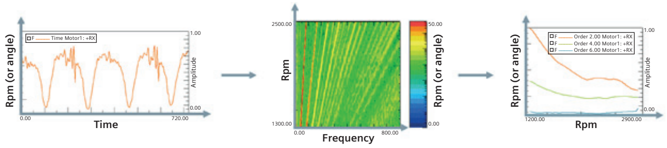


Figure 22. RPM tracking for time domain Fourier analysis.

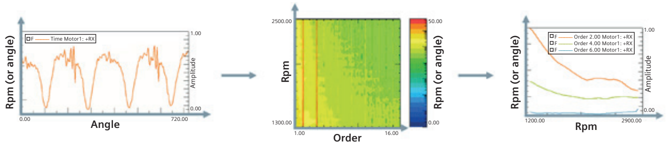


Figure 23. RPM tracking for angle domain Fourier analysis.

Angle-domain analysis

For the detailed analysis of events occurring at a particular phase of the system cycle, such as combustion-ignition timing in an engine, angle-domain analysis aligns all measured signals to the same angle-reference axis.

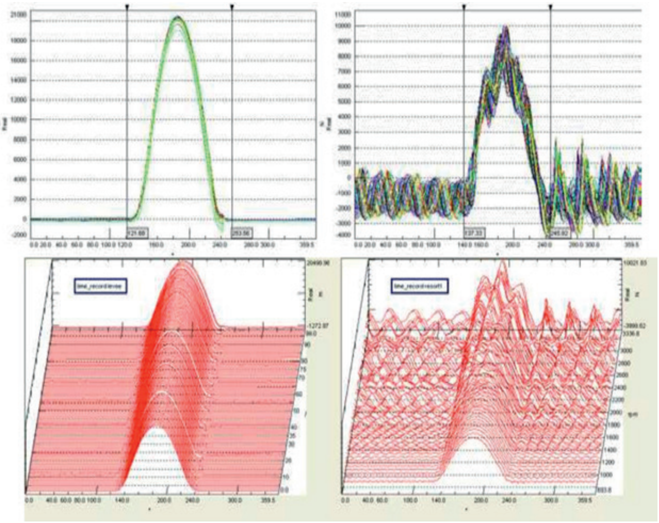


Figure 24. Shown is the combustion pressure and the valve displacement to the angle position of the crank shaft versus RPM.

Torsional animation

The interpretation of the measurement can be simplified with a good visualization of the deformation on o 3D geometry of the test object. Animating the deformation at a fixed frequency or according to measured torsional orders allows you to better qualify the importance of the phase relation between the different shafts or sections of shaft and vibration or acoustic responses. For transient phenomena, it's often preferable to directly animate the measured time-domain data.

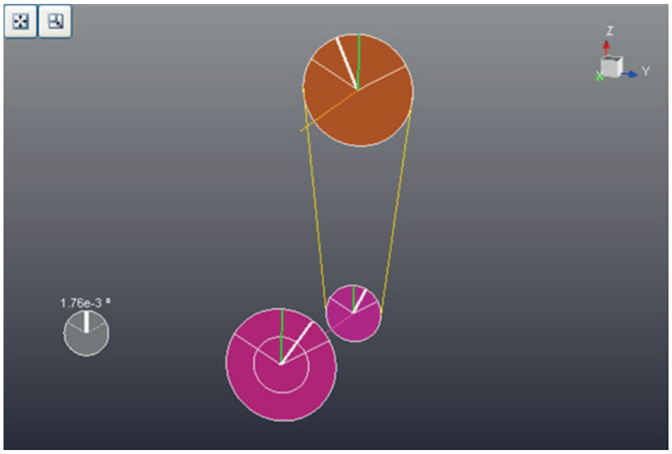


Figure 25. Torsional animation.

Annex 1

Tips and tricks for proper installation of zebra tape
To ensure proper measurement, even taking into account the automatic correction by LMS Test.Lab™ software for noise and vibration, there is little advice to follow when gluing zebra tape.

Zebra tape should be stuck well on the shaft and show a high-quality print, so it must be very accurate, which means it is must be perfectly striped. One point of great attention when gluing zebra tape is the joint of the two extremities. The LMS algorithm works very efficiently as soon as it needs to correct one error per rotation. It requires that only one stripe on the complete rotation is different than the others. Figure 1 shows the ideal configuration for the correction. In all following figures, black and white colors can be inverted with same result quality.

Figure 1. Ideal Zebra tape configuration.

Figure 2 shows another acceptable configuration. But due to the fact that the only affected stripe is smaller than the others, the correction quality could be lower, especially for relatively fast rotation. It's recommended to use a small piece of tape (figure 3) to get a similar situation as in figure 1.

Figure 2. Acceptable but not optimal configuration.

Figure 3. Ideal configuration using additional piece of tape.

The reality is typically more complex and most often two consecutive stripes will be affected as shown in figure 4. Again the easiest solution is to use an additional piece of tape to come back to the optimal configuration (figure 5).

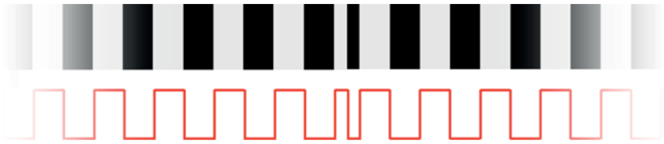


Figure 4. Correction algorithm does not work when two consecutive stripes are affected.

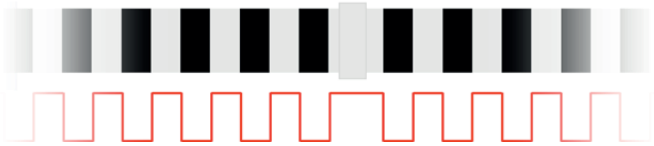


Figure 5. Ideal configuration using additional piece of tape.

It is a good practice is to avoid tape extremities that overlay each other. Since the tape has a certain thickness, the outer diameter of the coder will vary depending of the number of overlaid layers. The left configuration in figure 6 shows an example of the variation of the coder-angle resolution in the function of the number of tape layers. The second configuration is preferred for the LMS automatic correction algorithm.

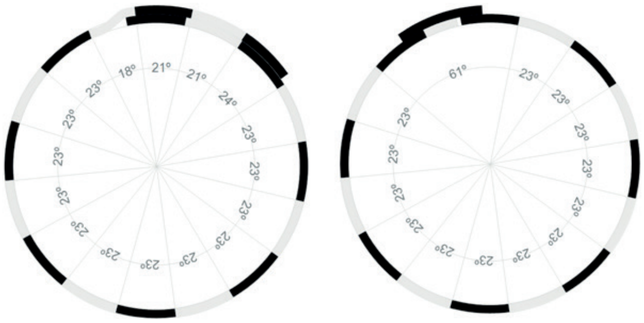


Figure 6. Wrong configuration with multiple errors per rotation (left) and preferred configuration with only one error (right).

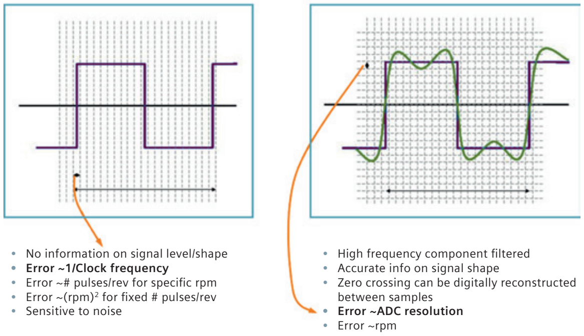
Annex 2

Pulse detection techniques

Accurate torsional analysis based on coders requires accurate estimation measurements of the pulse timing or tacho moments. The pulse-detection techniques must be adapted to the signal generated by the sensor.

Digital tacho (counter)

When the torsional sensor delivers a well-conditioned signal (TTL/RS422/RS485), the usage of a high-rate digital counter allows for the detection of a high-pulse rate. This technique checks the signal level at fix-clock rates and identifies a new pulse when the signal goes from low to high level between two consecutive samples. The accuracy of the pulses is equal to the inverse of the clock frequency.



- No information on signal level/shape
- **Error ~1/Clock frequency**
- Error ~# pulses/rev for specific rpm
- Error ~(rpm)^2 for fixed # pulses/rev
- Sensitive to noise

- High frequency component filtered
- Accurate info on signal shape
- Zero crossing can be digitally reconstructed between samples
- **Error ~ADC resolution**
- Error ~rpm

Figure 1. Digital and Analog pulse detection technique.

Analog tacho

Many sensors deliver a non-conditioned signal. The shape depends on the sensor technology used. Technology based on counters does not give sufficiently accurate results anymore. Siemens PLM Software developed a technology based on advanced digital-signal processing. The technology limits the pulse rate to 40,000 pulses per-second, but with the same accuracy as a digital counter applied on a well-conditioned signal.

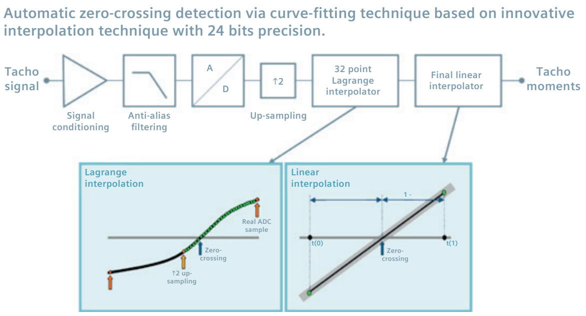


Figure 2. Pulse detection base on advanced curve-fitting for analog tacho.

Tacho reconstruction algorithm

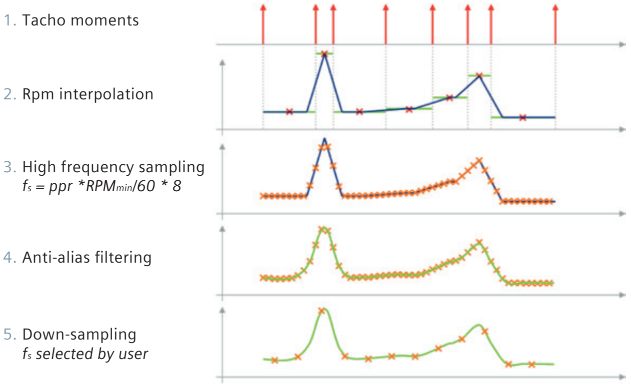


Figure 3. Effect of the tacho reconstruction algorithm on the signal.

The reconstruction algorithm converting the coder signal to a time equidistant RPM or angle curve is determinant in the quality of the Fourier analysis of the torsional vibrations.

1. A coder is used to get the timing of a fixed angle position. Each time stamp or tacho moment gives the angular position at a measured time. The exact angular position between two tacho moments is unknown. The average rotational speed between two tacho moments can be derived from angular positions. The reconstruction algorithm will assume that the number of pulses-per-rotation is sufficient to capture the complete signal behavior according to the Nyquist-Shannon theorem applied to angle domain sampling.
2. A linear interpolation is used to estimate the RPM between the known samples. The linear interpolation preserves the angle increments between two tacho moments.
3. The interpolated curve is sampled at a frequency that is higher than the maximum frequency theoretically measurable by the coder for the complete RPM range.
4. A low-pass filter is applied to remove all content generated by the interpolation and cannot be measured by the coder.
5. The signal is finally down-sampled to the desired frequency for processing.

Siemens Industry Software

Headquarters
Granite Park One
5800 Granite Parkway
Suite 600
Plano, TX 75024
USA
+1 972 987 3000

Americas
5755 New King Court
Troy, MI 48098
USA
+1 248 952 5664

Europe
Researchpark Haasrode 1237
Interleuvenlaan 68
3001 Leuven
Belgium
+32 16 384 200

Asia-Pacific
Suites 4301-4302, 43/F
AIA Kowloon Tower, Landmark East
100 How Ming Street
Kwun Tong, Kowloon
Hong Kong
+852 2230 3308

www.siemens.com/plm

About Siemens PLM Software

Siemens PLM Software, a business unit of the Siemens Industry Automation Division, is a world-leading provider of product lifecycle management (PLM) software, systems and services with nine million licensed seats and 77,000 customers worldwide. Headquartered in Plano, Texas, Siemens PLM Software helps thousands of companies make great products by optimizing their lifecycle processes, from planning and development through manufacturing and support. Our HD-PLM vision is to give everyone involved in making a product the information they need, when they need it, to make the smartest decisions. For more information on Siemens PLM Software products and services, visit www.siemens.com/plm.

© 2014 Siemens Product Lifecycle Management Software Inc. Siemens and the Siemens logo are registered trademarks of Siemens AG. LMS, LMS Imagine.Lab, LMS Imagine.Lab Amesim, LMS Virtual.Lab, LMS Samtech, LMS Samtech Caesam, LMS Samtech Samcef, LMS Test.Lab, LMS Soundbrush, LMS Smart, and LMS SCADAS are trademarks or registered trademarks of Siemens Industry Software NV or any of its affiliates. All other trademarks, registered trademarks or service marks belong to their respective holders.

36423-Y5 8/14 H