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Transmission error: the metric for gearbox NVH quality

The transmission error of a gearbox is the expression of the difference between the theoretical angular position of the driven gear (output shaft) and its actual position while running the driving gear (input) at constant speed.

The transmission error quantifies the gearbox's imperfections when transferring energy from input to output, resulting in a metric of the gearbox's efficiency. The higher the transmission error, the higher the risk of an amplified dynamic variation of the shaft's rotational speed or torque. This would imply an increased risk of noise or vibration problems in the gearbox or elsewhere in the driveline. For example, a high deflection of gear teeth at the impact moment could lead to an increased transmission error and may excite a resonance of the shaft.

The transmission error is assumed to be the most important index for gear NVH quality. Not surprisingly, it is not only measured in order to troubleshoot gearbox NVH issues, but it is also used as quantity for target setting, benchmarking or correlation with simulation results.

The main causes of transmission error are:

- Gear mesh inaccuracies, such as gear eccentricity, unequal tooth width or pitch deviations. These can be reduced thanks to smart gear design and improved manufacturing processes.
- Local gear teeth deflections (due to local flexibility), which could result in noise problems like gear whine.

In practice, the transmission error will be measured experimentally and at different operating conditions (different loads). The transmission error is usually expressed as:

Te = rpmout – rpmout, theoritcal = rpmout – rpmin / tr

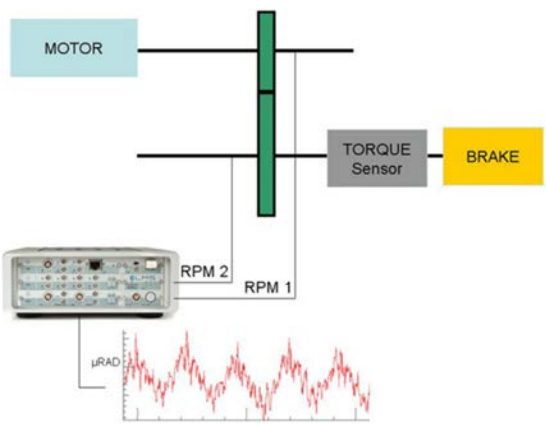
with tr being the transmission ratio of the gear set. Therefore, measuring the transmission error implies a measure of the driving and driven shaft's rotational speeds. Often the transmission error is integrated to be expressed in angle (degrees), instead of rpm.

In order to measure these values correctly, the angular position or speed of both input and output shafts need to be acquired with extremely high accuracy as the variation levels are very small in amplitude. The full measurement chain is important to ensure greatest accuracy. Different types of coder-based sensors, such as magnetic pick-ups, or optical sensors may be used, in combination with the LMS SCADAS RV4 module and LMS Test.Lab.

For practical reasons, in case of in-situ gearbox measurements, the gears themselves are used to measure the angular speed, by means of magnetic sensors capturing the passing frequency of gear teeth. However, capturing higher frequency rotationalvariations will require more pulses per revolution. In this case, it is likely that the number of gear teeth is insufficient and that other markers will be required. Zebra tape, in combination with optical sensors, is a valuable alternative to drastically increase the accuracy.

In their development phase, gearboxes are typically tested and optimized on dedicated test rigs, where the transmission error can be measured according to different gear operating conditions. The rotational speed is often captured by means of incremental encoders, which are part of the test rig.

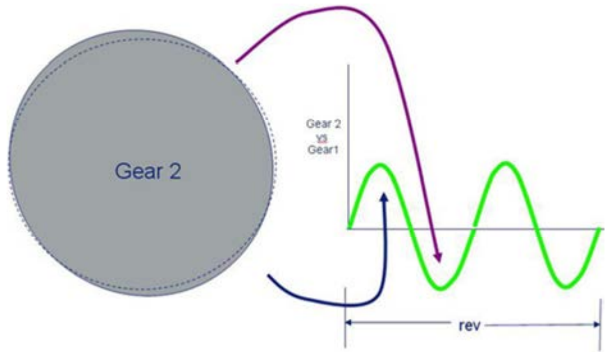
A schematic of a rig is shown below: the transmission error of a specific gear pair can be measured in function of the applied torque, but potentially also in function of some artificially applied manufacturing inaccuracies, such as shaft misalignment. The latter would help identify the limits of manufacturing tolerances.



The test typically yields transmission error estimation in function of the driven shafts angular position. The maximum transmission error within a cycle quantifies the gears quality in the specified condition.

How to interpret the measured transmission error? Not only is its amplitude of interest, but also its power spectrum, which provides more insight in the causes of high error:

- A high first order contribution for example often indicates gear misalignment. In this case, the gear's rotational center deviates from the geometric center, causing the gear acceleration and deceleration within one cycle.
- A dominant second order contribution indicates gear eccentricity, which lets the gear accelerate and decelerate twice within one cycle.

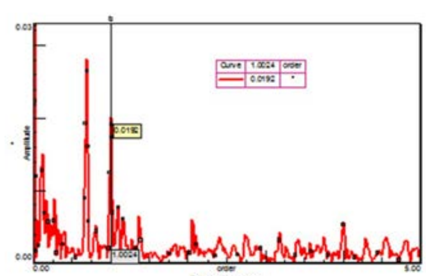


Second order variation in rotational speed

- When gear teeth are loaded, the teeth may locally bend. This has an impact on the gears' speed, leading to an order contribution number equal to the number of teeth and a dominant order in the transmission error spectrum. This frequency is named the gear meshing frequency (or gear meshing order).

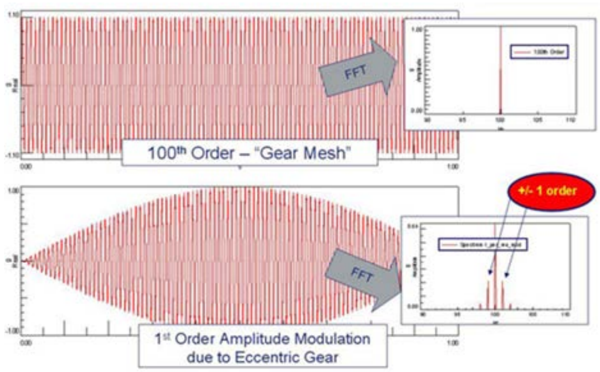
$$\mathbf{fmeshing = frpm \cdot n}$$

In practice, the transmission error will result from a combination of different phenomena and the interaction between these phenomena will lead to a more complex power spectrum.



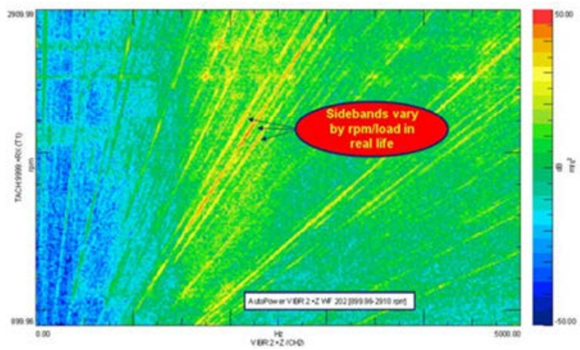
Example of power spectrum of measured transmission error

For instance, a gear whine problem combined with gear misalignment will classically lead to modulation phenomena in the spectrum. Typically, the spectrum will show sidebands around the gear meshing frequency.



Theoretical example of transmission error: combination of gear whine and gear misalignment

The example below shows how the gear meshing frequency and its sidebands appear into the vibration spectrum of a transmission. Similar phenomena may be found in the noise spectrum and in the spectrum from the transmission error itself.



The transmission error is not only relevant for gearboxes, but also for any power transmitting element, such as the belt or chain driver frontend accessories of an engine. Measuring the errors in transmission between the engine's crankshaft and shafts of driven components such as cam shaft, alternator or fuel pump delivers valuable information on how to further improve the frontend accessory drive.