Measuring gear transmission error inside a loaded, running gearbox is the perfect tool for detecting and diagnosing gear noise. Romax Technology explains.

By Dr. Michael Platten
NVH engineers are used to measuring things. Any NVH—for “noise, vibration, harshness”—lab you visit will likely as not be stuffed full of accelerometers, microphones, tangled heaps of cables, and analogue-to-digital data acquisition systems. However, ask the NVH engineer sitting hunched over the computer in the corner to measure transmission error (TE) and they will probably give you a blank stare and a shrug. In fact, for transmission design and development, TE is the single most important parameter defining gearbox noise quality. This is why, as a gearbox NVH engineer, it is something I spend a lot of time measuring—and why you should consider it, too.

WHAT IS TE?
TE is the source of gear whine noise. A simple definition of TE is “the difference between where you expect the gear to be and where it actually is.” A perfect gear pair transmits motion smoothly. In fig. 1a the driving gear is being rotated at constant speed, and the driven gear also moves at a constant speed determined by the gear pair ratio (2:1 in this case). This is called “conjugacy of motion” and comes from the fact that these are true involute gears.

Real gears, on the other hand, are not perfect. They are not manufactured perfectly, and the teeth deflect under load. The shafts and bearings on which they are mounted deflect under load and misalign, and of course we make deliberate modifications to the gears like crowning, tip relief etc.; all of which means that the gears are no longer of perfect involute shape, so even when the driving gear moves smoothly the driven gear does not (fig. 1b). There is an “error” in the ideal smooth “transmission” of motion. These forced variations in gear rotational position are cyclic and occur every time a tooth passes through the mesh.

This is an example of a “self-excited vibration.” The excitations travel through the shafts and bearings to the housing where they are either radiated as noise, or the vibrations travel through connections to other parts of the structure where they can also cause noise. It is this noise that we call “gear whine.”

Although TE is an error in rotational position, for convenience it is usually expressed as a linear distance at the base or pitch radius of the gears. In 99 percent of cases, it has an amplitude somewhere between 0.1 μm and 10 μm.

WHY MEASURE TE?
Gear whine is a quality issue. No gearbox has ever broken because it had a gear whine problem. However, quality—or at least perceived quality—is critical to customer satisfaction, particularly in the automotive industry. So a whiney gearbox is a bad gearbox, even if it is perfectly fit for purpose from a functional point of view.

It is a fundamental principle of noise control that the best approach to improve noise

![Fig. 1: Smooth transfer of motion in an ideal gear pair (a) and non-smooth motion in a real gear pair (b).](image)
Driving gear pulses

Expected driven gear pulses

Actual driven gear pulses

Fig. 2: Rotary encoder pulse trains used to measure TE.

in a system is to mitigate the source of that noise. With gear whine, that source is TE; reduce the TE and the noise is reduced proportionally. You can see why any tool that helps us investigate and understand TE is a useful thing to have. Among other things, measuring TE helps us to:

- Troubleshoot—investigate the cause of a gear whine problem at the component level along with traditional NVH measurement techniques;
- Set targets—identify what constitutes an acceptable/unacceptable amount of TE for our application;
- Benchmark—compare one design against another or against a competitor;
- Correlate—compare predictions of gear analysis predictions from software like RomaxDesigner with reality;
- Redesign—quantitatively assess the effectiveness of design changes in improving NVH performance at the most fundamental level, and;
- Assure quality—identify the impact gear manufacturing quality and variability have on noise quality.

MEASURING TE

Remembering the simple definition of TE—"the difference between where you expect the gear to be and where it actually is"—it is easy to see how we measure TE: measure the rotational position of the
driving gear. From that result calculate the expected rotational position of the driven gear using the gear ratio. Compare this with the measured rotational position of the driven gear. The difference is the TE.

Although this appears simple enough, in fact we are trying to measure something to sub-micron levels of accuracy, so it needs to be done with care. Incremental rotary encoders are the transducers used to measure gear rotary position. These devices produce a digital pulse several thousand times per revolution (5000 pulses per revolution is typical and >20000 is possible, but expensive) at very accurately spaced intervals. Figure 2 shows what happens next.

The driving gear is, in this case, rotating at a constant speed so the spacing of the pulses is equal. From this pulse train we can calculate what we expect the pulse train from the driven gear to look like. For this example the ratio is 2:1, so we expect the driving gear pulses to be “stretched” by a factor of two, as shown in the diagram. However, the pulses we actually measure from the driven gear are nearly but not exactly what we expect. The difference between the “expected” and “actual” driven gear pulse train is related directly to the TE.

There are several different methods by
which the TE information can be extracted from the pulse trains. The method used by the Romax TE Measurement System (fig. 3) is the most robust method, and also the easiest to understand.

As its name suggests, the “velocity” method of TE measurement works by measuring the rotational speed of the shafts. This is done by very accurately measuring the time from one pulse to the next. We know the spacing of the pulses as there are a fixed number per revolution, so we can easily obtain the velocity. The velocity can be integrated to obtain the rotational displacements. The driving gear displacement is multiplied by the gear ratio to get the expected driven gear displacement. This is then subtracted from the actual measured driven gear displacement to get the TE.

The only disadvantage with this approach is that a normal analogue-to-digital data acquisition system cannot measure the time between the pulses accurately enough; a specialist dedicated (though not necessarily expensive) data acquisition system is needed. The Romax TE Measurement System measures the time between pulses with a precision of 1/100,000,000th of a second.

**PRACTICAL TE MEASUREMENT**

Ideally, we want to measure the TE under near-operational conditions; i.e. with the gears inside the gearbox, and with the gearbox rotating under load. There is sometimes a benefit in measuring the TE of a simple gear pair on its own where we are interested in a very detailed analysis, for example comparing the effect of different machining or finishing methods on gear performance. It is also a simpler setup than that for an in-situ test, so we can see more clearly what is going on.

Figure 4 shows the setup for a real test. The gears are mounted on custom-made spindles that are set in precision bearing blocks. Rotary encoders are connected to the spindles, and the driving gear spindle is rotated slowly (<10 rpm) via a belt by an electric motor. This is a no-load test, but a very small load is applied to the driven gear by the drag from a cord wrapped around the driven gear spindle with a small weight attached. This stops the gear teeth from losing contact, but does not add any significant load. Everything is very carefully mounted to very tight tolerances to ensure that there is no misalignment of the gear.

Although useful, these isolated gear pair tests are not usually representative of the true in-service conditions experienced by a gear pair. In-situ gears are subject to varying loads, deflections, and misalignments, all of which affect the TE.

Most of the TE measurements that I carry out are performed on automotive gearboxes, so the in-situ test described here reflects that. There is no reason in
The principle why we could not measure TE with the gearbox in the vehicle. However, there are practical reasons why this is not done. Firstly, we need to accurately control the torque through the gear pair (variation of TE with torque is one of the things we are often most interested in). Secondly, we are trying to measure what is known as the “static” transmission error. Static TE is the TE that is unaltered by the dynamic behavior of the gearbox and the vehicle. In practice this means that we have to measure the TE at a rotation speed of about 250 rpm or less, which is not possible in a real vehicle. Mounting the gearbox on a dynamometer test stand allows us to accurately control both the speed and the torque.

The next practical difficulty is how to connect the encoders to the gears. There is not a lot of space inside a gearbox to mount a typical encoder, so instead we extend the gearbox shafts outside the housing. This can be seen in fig. 5. Special couplers are used to connect the shafts to the encoders. The encoders are sensitive to small misalignment errors, and the use of the couplers combined with tight tolerances in the design and manufacture of the encoder mounts helps to minimize any errors.

**INTERPRETING RESULTS**

So we have measured some TE. Now what? Figure 6a shows a typical result. This shows the TE for one revolution of the driven gear averaged over a number of revolutions. The TE is dominated by an overall cyclical variation that happens once per revolution. This is caused by runout and cumulative pitch errors in the gear. Usually we are not interested in this as it causes gear whine vibrations at a frequency that is too low to be a nuisance, although it can alter the character of gear whine noise by a process known as “modulation.”

The parts we are predominantly interested in are the smaller variations that happen at each tooth engagement. There are 37 of these blips per revolution, corresponding to the number of teeth on this gear. Notice that the TE varies from tooth to tooth; some show a peak-to-peak range of over 10 μm where others are less than 5 μm.
We can average these results further so that we have the average TE per tooth. This allows us to quote a single figure value for the peak-to-peak TE (about 0.85 μm in this case) but we must be aware that there is a large degree of variability associated with this value as the un-averaged results have shown us.

NVH engineers like to think in terms of frequencies, harmonics, and orders. It is how we investigate and interpret noise problems like gear whine. For this reason, and to avoid any ambiguity, we can perform spectral analysis on the TE signal to break it down into its individual frequency components. The result of this for our 37-tooth gear can be seen in fig. 6a. It is clear that the largest contributing factor is from the first harmonic (once per tooth) component; higher components exist at twice and three times per tooth, but these are much smaller. So we would quote this gear as having an “average TE amplitude of 0.42 μm for the first harmonic”—a clear, unambiguous, and useful result. If the other harmonics were significant then we would quote them too.

**SUMMARY**

Accurate measurement of transmission error is the key to successful improvement of gearbox NVH quality. Controlling the NVH quality of geared systems, and ultimately improving customer satisfaction in the end product, requires the ability to understand and control TE. Tools like the Romax TE Measurement System enable you to accurately measure and analyse the TE behavior of gearbox systems under load and in situ. You can then use this data to objectively assess noise and vibration performance and identify potential problems under near-operational conditions.

The intention of this article is to show that, although not widely practiced, the measurement of TE is not a black art, and it could and should be used on a regular basis as part of any gearbox design, development, and improvement program.

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**Fig. 6a:** Results from a real TE measurement showing TE for 1 revolution of the driven gear.

**Fig. 6b:** Results from a real TE measurement showing harmonic spectrum of the averaged TE signal.

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