MARPOSS

WHITE PAPER

# SINGLE FLANK & NVH TEST FOR EV GEARS QUALITY CONTROL

# CONTENTS

## ABSTRACT

The production and use of gear wheels in power transmission is related to three general characteristics related to their application: manufacturing accuracy, meshing noise and reliability. From a quality control perspective, realization accuracy and meshing noise can be monitored by analyzing the transmission error and certain parameters that can be calculated from it. This paper analyzes the types of tests (single flank and NVH) that can be used for this purpose; some interpretative keys are given for the results that can be obtained in relation to the most common manufacturing errors.

## INTRODUCTION

With the increasing popularity of electric motors in drive systems, the control of noise, vibrations and harshness (NVH) has become an increasingly critical aspect of powertrain design. Compared to internal combustion engines, electric motors are quieter and operate at higher rotational speeds. This new operating condition highlights vibrational phenomena that were previously negligible, making even low-frequency components, such as the first-order meshing of gear wheels, audible inside the cabin. To effectively address these aspects, it becomes essential to analyze the dynamic behavior of transmissions.

Power transmissions are complex systems made up of numerous components. Of these, the gear wheels are the best-known element, but their proper functioning requires the presence of other components such as shafts, bearings, gearboxes and frames. All these elements, interacting with each other, determine the transmission's own frequencies.

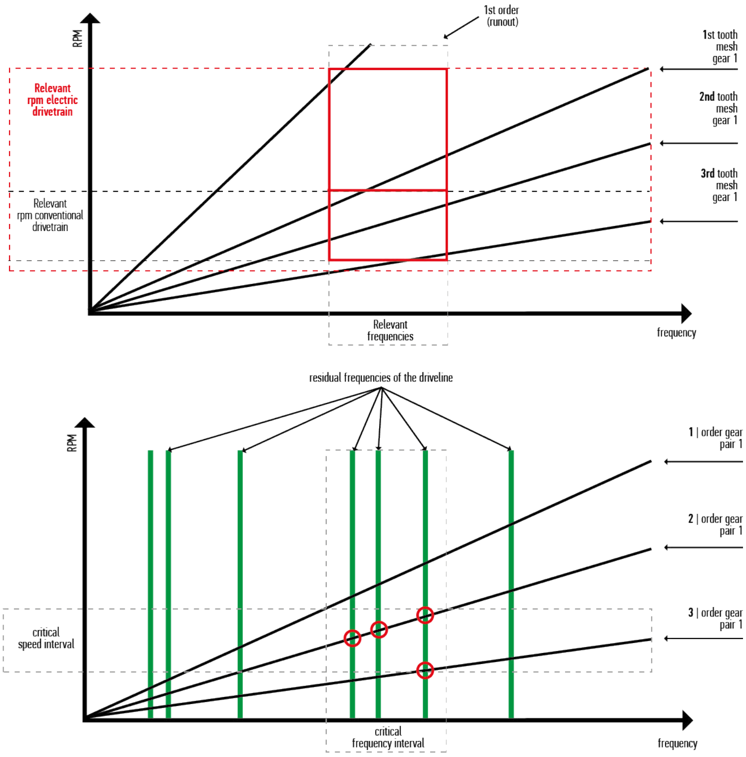



**Figure 1** - Campbell Diagram

A particularly useful tool for this analysis is the Campbell diagram (Figure 1), a graphical representation that shows the course of the system's natural frequencies as a function of rotational speed. These frequencies, which depend on the configuration and elastic characteristics of the transmission, can be calculated using CAD software or by means of finite element analysis (FEM). In the diagram, these frequencies appear as vertical or slightly curved lines, while the excitation orders generated by the gears (e.g. H1) are represented by oblique lines.

The intersection point between a natural frequency and an excitation order identifies a critical velocity — i.e., a condition in which resonance may occur with potential negative effects on noise, vibration and structural integrity. In the diagram, the red circles highlight some of these critical conditions, particularly within the typical operating areas of the system and in the frequency range audible to humans (approximately 20 Hz - 20 kHz). Early detection of these areas is essential to prevent the excitation produced by the gears from activating the driver's own vibration modes.

In light of the above, it might seem that the solution is simply to eliminate the vibrations caused by meshing. In theory, this would only be possible in the ideal case of perfectly manufactured involute gears mounted on infinitely rigid supports. However, in operational reality, several factors come into play: contact forces between the teeth, external stresses, and elastic deformations of the entire kinematic chain. Added to these are the inevitable construction tolerances that cause misalignments between the gears. All these effects lead to transmission errors, which result in vibrations and noise.

Historically, in order to mitigate these phenomena and improve the vibrational behavior (NVH) of transmissions, action was taken by modifying the shape of the gear tooth profile in order to ensure a more controlled and progressive contact between the teeth during meshing. These geometric modifications, known as profile corrections (Figure 2), are implemented as follows:

- Modifications such as end relief, lead crowning and profile twist are used to compensate for axis misalignment.
- Modifications such as profile crowning and profile twist are used to compensate for tooth bending.


**Figure 2** - Possible modifications to the shape of tooth flanks of involute gears [3]

The modification of the gear tooth profile, introduced to improve the dynamic behavior of the transmission, inevitably leads to the occurrence of a transmission error (TE = Transmission Error). In an ideal case, with perfect involute profiles and no deformations, this error would be zero. However, in practice, each geometric modification aimed at optimizing the contact between the teeth introduces a periodic variation in the transmitted motion. This periodicity of the transmission error is one of the main sources of excitation of the gearbox's vibration modes: in other words, the very design of the gearwheel becomes the origin of structural vibrations.

Adding to this, design choices are manufacturing errors, which arise from the inevitable tolerances of the production process and further contribute to the shape of the transmission error. These include:

- Run-Out (rotation oval) of the wheel
- Pitch diameter deviations
- Indexing errors (teeth angular misalignment)

When a load torque is applied to the gearing, the shape of the transmission error is altered due to the elastic deformation of the components. However, its basic frequency structure remains unchanged

(Figure 3), continuing to generate excitations in the same frequency bands.

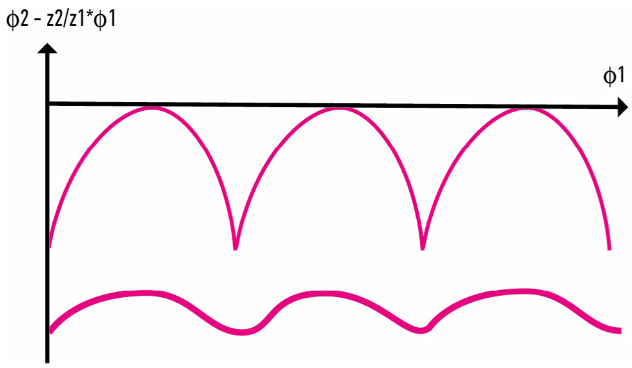



Figure 3 – Transmission error of a test gear measured without torque (thin line) and with torque applied (bold line)

With regard to wheel noise testing, in "classic" automotive production, it has always been considered sufficient to check the transmission error without the application of torque, [3] but increasingly this check is being accompanied by an NVH test.

One method of describing the transmission error mathematically and analyzing it in detail is to decompose it into Fourier series (order decomposition). The frequency spectrum obtained (Figure 4) highlights the main contributions to the transmission error, the most important of which are certainly the harmonics corresponding to the number of teeth and its multiples (Figure 4-a). But other defects are visible in different areas of the spectrum, e.g., the presence of a runout causes the appearance of an order one in the frequency spectrum and two side-bands at the sides of the orders, corresponding to the number of teeth and its multiples (Figure 4-b); whereas, an order two in the primitive diameter causes the appearance of order two in the frequency spectrum and four side-bands at the sides of the orders, corresponding to the number of teeth and its multiples (Figure 4-c).

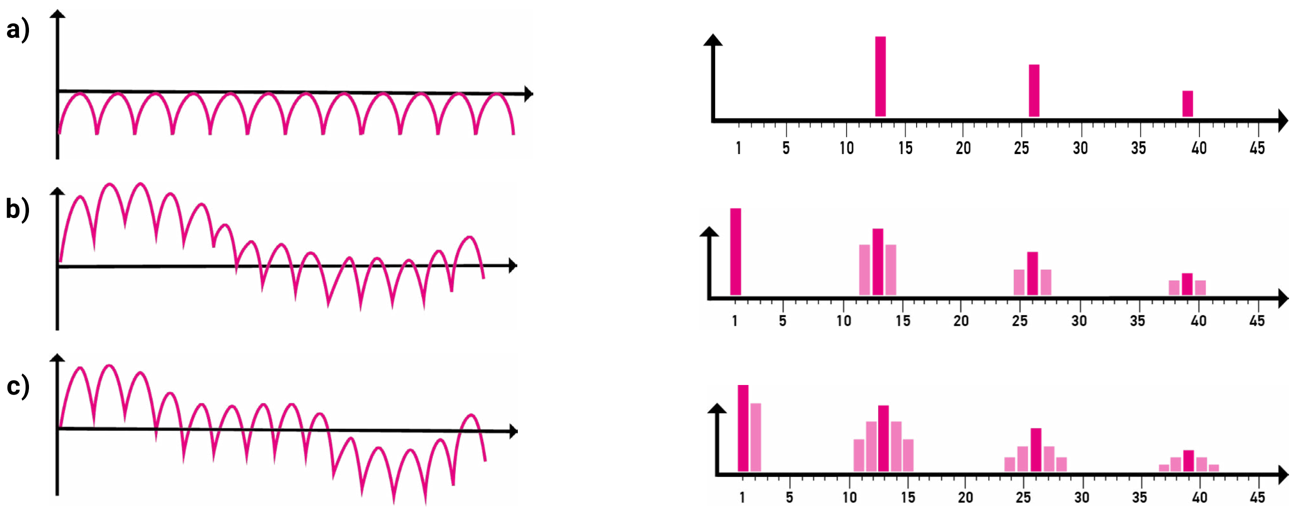



**Figure 4** – Representation of the effect of production defects on the frequency spectrum of the transmission error

Currently, the characterization of transmission error is mainly done by means of a rolling test, performed on dedicated test benches. Depending on the objective and the required level of accuracy, four main types of test are available, each with specific advantages and limitations, a general overview of which is given below:

- Double Flank Test (DF): is a simple and quick test method for assessing some fundamental characteristics of the gear. However, it is a rudimentary technique, unsuitable for predicting the acoustic behavior of a gear wheel, and therefore of little use in NVH assessments.

- Single Flank Test (SF): is a more complex and accurate test that allows the measurement of transmission error under controlled contact conditions. Although it takes longer to perform, it is a very effective tool for predicting the vibroacoustic behavior of gears.
- NVH - Structure-Borne Noise (SBN): is a fast and sufficiently accurate test based on the detection of structure-borne noise. However, the results are highly dependent on the measuring instrument used, which makes it difficult to compare data obtained with different instruments, even if they are nominally identical.
- NVH - Torsional Acceleration Test (TA): is a test that allows a quick and accurate assessment of the dynamic behavior of the transmission by measuring the torsional acceleration of the shaft. An important advantage of this technique is its low sensitivity to the influence of the measuring instrument, which guarantees greater repeatability and comparability of results.

In the industrial production of gearboxes for electric vehicles, a new standard of in-line quality control is emerging, based on the integration of two test techniques: the Single Flank Test (SF) and the NVH test with torsional accelerometer (TA). The combined use of these two methodologies offers an excellent balance between measurement time, accuracy and data robustness. It proves particularly effective in supporting process engineers in monitoring and reducing gearbox noise.

Electric drive (e-Drive) applications introduce specific requirements that set these transmissions apart from traditional internal combustion systems. In particular, both tooth flanks - the active (driving) and the passive (coasting) – must be considered equally important for vibroacoustic quality. In electric drivetrains, energy flow in both directions: from the motor to the wheels during acceleration, and from the wheels back to the battery pack during regenerative braking. As a result, the transmission must ensure low noise and vibration in both load directions.

For this reason, the traditional Double Flank Test, once useful for dimensional and functional checks, has lost its relevance. It is no longer sufficient to detect asymmetrical behavior between the two flanks of the tooth. Today, it is increasingly being replaced by more sensitive and informative methodologies, such as the Single Flank Test or the Transmission Error analysis combined with NVH tests, which provide detailed insights into the acoustic behavior of the system under real operating conditions.

The combination of rolling test (SF + NVH) and dimensional/geometric measurement – using coordinate measuring machines (CMMs) or gear measuring machines (GMMs) – enables a comprehensive quality approach. The former prevents noisy gears from being installed in transmission, while the latter helps analyze problematic parts and trace back issues to specific steps in the production process.

## SINGLE FLANK GEAR TEST WITH ENCODER (TE TEST)

As its name suggests, the Transmission Error (TE) Test is designed to quantify the transmission error introduced by a sample gear within the drivetrain where it will be used. To carry out this measurement, the gear is paired with a highly precise reference master gear (Rolling Master, RM).This master gear is manufactured to a very high standard (low DIN grading) to minimize key geometric deviations such as profile, helix, pitch and run-out errors.

In an ideal scenario - where both the master gear and the RM are perfect, featuring pure involute profile without any modifications – motion transmission would be completely uniform and predictable. However, under real-world conditions, the transmission error is defined as the difference between the instantaneous (actual) angular position of the gear being measured and the ideal theoretical position it should occupy at any given time. This deviation reflects the cumulative effect of all geometric errors present in the component.

The outcome of the test is typically presented in two separate graphs, each corresponding to one of the two tooth flanks: the right flank (drive) and the left flank (coast) (Figure 5 shows the graph of one of the two flanks). In ideal conditions, these graphs would appear as flat horizontal lines with zero variation. A.ny deviation from this trend would indicate the presence of abnormalities in the gear teeth.

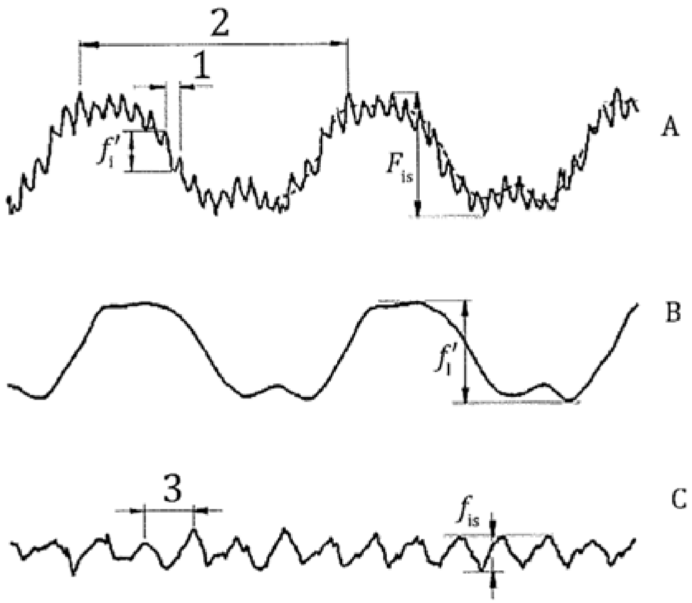



Figure 5 – Typical appearance of a single-flank gearbox acquisition and measured quantities [1]. Graph A represents the total tangential compound error, B the long-period component, C the short-period component obtained by subtracting curve B from curve A; 1 indicates the amplitude of a single pitch, 2 corresponds to a complete rotation of the workpiece and 3 represents a single pitch in the graph of the short-period component

During the test, the RM is brought to a predefined radial distance from the test gear (indicated as “a’” in Figure 6) to ensure controlled contact with only one flank at a time. Both axes (RM and test gear) are equipped with high-resolution rotary encoders and the transmission error is obtained as the difference between the angular signals acquired by the two encoders.

To ensure contact stability during rotation, a resisting torque must be applied. This can be  generated either passively using a brake or actively motorizing both axes. This appliedtorque must be sufficient to prevent detachment between the sides (flank separation), but without inducing local deformations.

The test is performed at low rotational speed, typically below 60 rpm for the small wheel [1].

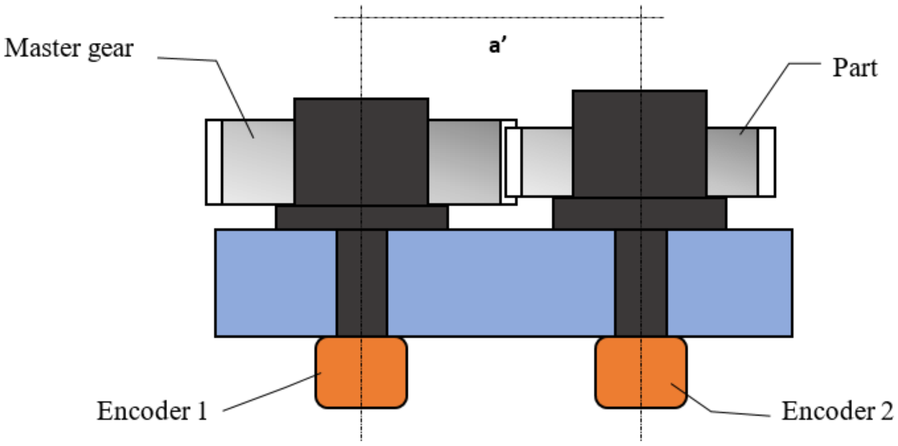



**Figure** 6 -Concept schematic of a single flank gear checker

The entire measurement cycle consists of two distinct phases: in the first, contact is made on the drive flank; in the second, the coast flank is analyzed. For each phase, a transmission error vector is obtained. These vectors are valuable for comparative evaluations and the identifying potential non-conformities in the gear geometry or meshing behavior.

The Single Flank Test can also be performed between two sample gears, rather than between a test wheel and a reference master. In this case, it is no longer possible to neglect the elementary errors present on both components, as each wheel will contribute to the overall TE transmission error. To obtain a comprehensive and representative analysis of the meshing behavior, the measurement cycle must be extended over what is referred as the complete meshing period (hunting tooth period). This is the number of consecutive rotations that the smallest wheel must undertake for the initially engaged tooth pair to make contact again in the same angular configuration. Measuring over the full period ensures that all possible tooth pair combinations are explored, providing a reliable and repeatable assessment of the vibroacoustic behavior of the actual gear coupling - including the influence of distributed tolerances and manufacturing imperfections.

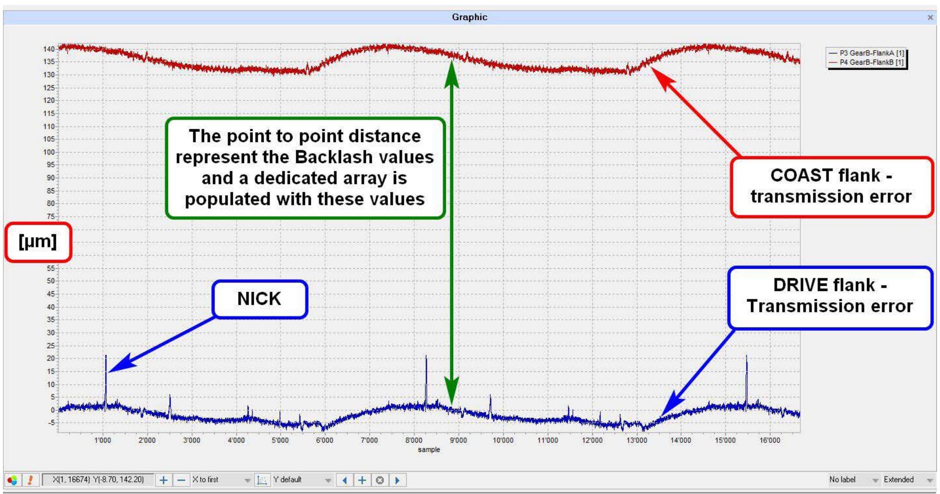



**Figure 7** - Typical appearance of the vectors on the Drive and Coast flanks of a single-flank gear.
The x-axis shows the degrees of rotation the gear being measured while the y-axis shows the µrad or µm of the drive error.

## SINGLE FLANK MEASUREMENTS DESCRIPTION

In this chapter we will describe how the main measurements of single flank gears are processed. The elaborations described refer to ISO standards: ISO/TR 10064-1:2019 Code of inspection practice [1] & ISO 1328-1:2013 Cylindrical gears [2].

*$F_{is}$ – Total single flank composite deviation*

Formerly identified with Fi', it is calculated for each flank as the range (max - min) of the transmission error vector appropriately filtered. It is possible to include the nicks in the calculation or exclude them according to analysis requirements. This measure represents the overall effect on the transmission ratio that elementary defects such as tooth eccentricity errors, tooth pitch irregularities, involute profile errors, and helix errors, as well as concentrated defects such as burrs or dents introduce.

As it is a range measurement, it is affected by the repeatability of the bench in determining the minimum and maximum points, so dirt or dents have a great influence on this measurement.

*$f_i'$ – tooth-to-tooth single flank composite (without removal of long-term component)*

When the number of samples per revolution of the workpiece and the number of teeth in the workpiece are known, it is possible to define a window, in samples, as wide as the pitch between one tooth and the next (see dimension 1 in Figure 5). Within the window thus defined, the range of this subset of $F_{is}$ samples can be calculated. The final measurement is the worst of the subsets identified or, less frequently, the average of all subsets. It may contain nicks within it according to the control requirements and, as a general rule, if the application includes the nick measure then $f_i'$ must be cleaned of nicks before calculating the final value. This measurement has lower tolerances and average values than $F_{is}$ and fl' and is a good indicator of pitch-related defects between teeth as well as profile, pressure angle and/or helix angle errors (generally speaking, errors on the involute profile).

The repeatability of this measurement depends on the quality of the master gear and the way it combines with the workpiece gearing.

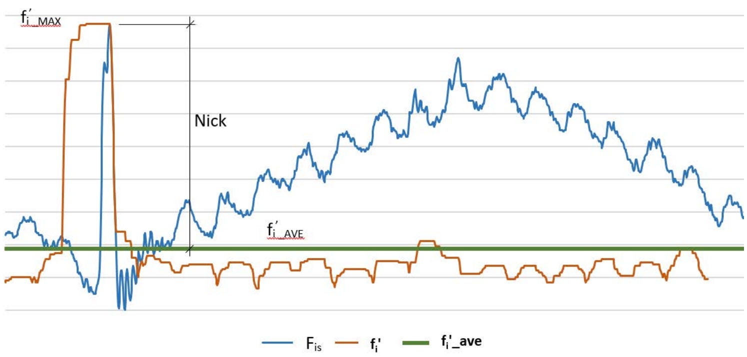



**Figure** 8 – Visualization of $f_i'$ max and $f_i'$ ave arrays generated from the $F_{is}$ array

*fl' – Tangential Runout (variance of the long period component over one revolution)*

The measurement of fl' contains the first 5 or 7 harmonics of the original signal and the output value is equal to the range of the vector thus obtained (alternatively, and in accordance with [1], fl' can be obtained with a wide moving average filter piece tooth number*tooth sample number*0.1 samples). In Figure 5, the vector of fl' is represented by curve B. The range of this measurement provides important indications of the "smoothness" of the transmission and is related to both the primitive diameter runout and the cumulative pitch error of the measured wheel.

As it is defined, this measurement cannot be further filtered out and is not affected by meshing, minor gear damage, or dirt.

*$f_{is}$ – tooth-to-tooth single flank composite deviation (after removal of long-term component)*

This quantity is conceptually very similar to fi' in that it is calculated on the step between one tooth and the next. Starting from the $F_{is}$ signal to which the long period component has been removed, a window as wide as the pitch is defined within which the range of this subset of samples can be calculated. The final measure is the worst of the subsets identified or, less frequently, the average of all subsets. It can contain the nicks within it according to the control requirements; as a general rule, if the application includes the nicks measure then $f_{is}$ must be cleaned of nicks before calculating the final value. The repeatability of this measurement depends solely on the quality of the master toothing and how it combines with the workpiece toothing, as well as dirt and defects.

*Nicks & Additional tooth-to-tooth action*

The nick represents isolated, large damage (large compared to the typical $f_{is}$ value for the parts under examination), typically due to burrs from machining or dents caused by impacts of the parts during transport. Damage could, in turn, cause an extra rotation or a reduced rotation so, in the $F_{is}$ graph, the nick can occur as either a positive or negative peak. The nick is generally handled with a threshold so that the measurement will be zero as long as it is below the threshold and will take on a non-zero value should the nick exceed the threshold.

It is also possible to handle denature damage in other ways that can be defined as additional tooth-to-tooth action or ATT. Unlike the nick seen above, there is no recognition threshold so this measure will always be a positive number. The recommended approach is always to consider ATT as the difference between the maximum fis value from which the average fis value is subtracted; similarly, $f_i$' and average $f_i$' can be operated on. See Figure 8 for more clarity.

In the production of gearboxes for electric vehicles, this measurement is present and, compared to the past, has undergone a considerable reduction in the value that identifies it. Whereas nick used to be indicated as a large isolated error (e.g. 80 µm) in EV gears it has a reduced value of 70-80%. This underlines the importance of producing gears without localized defects that would lead to noise problems in the gearbox.

*Backlash*

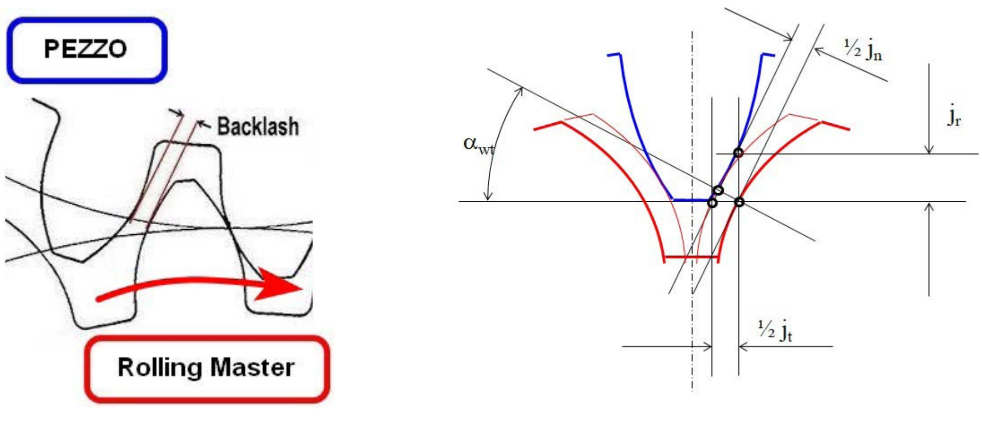



**Figure 9** – Backlash definition and decomposition in the three main directions

Tooth backlash is defined as the distance in [mm] between the non-contact flanks and can be defined according to 3 main directions: tangential jt, normal jn and radial jr as shown in Figure 9. Unless otherwise specified, tooth backlash is always referred to as tangential backlash jt in the transverse plane. The backlash measurement is represented as a continuous vector of which, in general, the average value or alternatively, the minimum value is calculated.

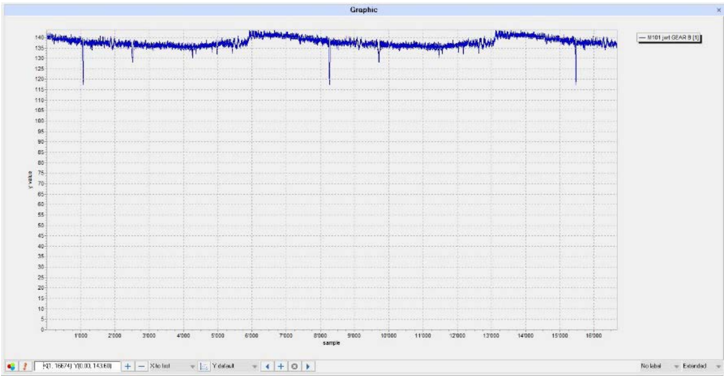


**Figure 10** – Backlash array example

The backlash between the teeth is a quantity that depends mainly on the interaxis (a' in Figure 6) at which the two gear wheels are working, and increases as the distance between the wheel centers increases. This measurement is affected by the variation in the dimension of the sample gear (see Figure 11), compared to the nominal value.

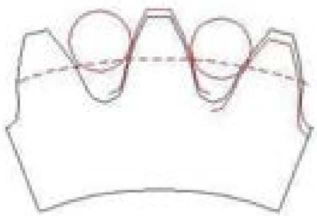


Figure 11 – Over ball diameter variation represented in adjacent teeth.

### *$f_{es}$ – Eccentricity*

Eccentricity is defined as the half amplitude of the first harmonic extracted from the $F_{is}$ vector (see Figure 12). This measurement provides an indication of the amount of off-center of the primitive gear diameter in relation to the references used during machining.

*Circularity*

Circularity refers to the vector obtained by starting from $f_l$' and subtracting the vector $f_{es}$ (see Figure 12). The result is comparable to a measure of circularity of the primitive diameter.

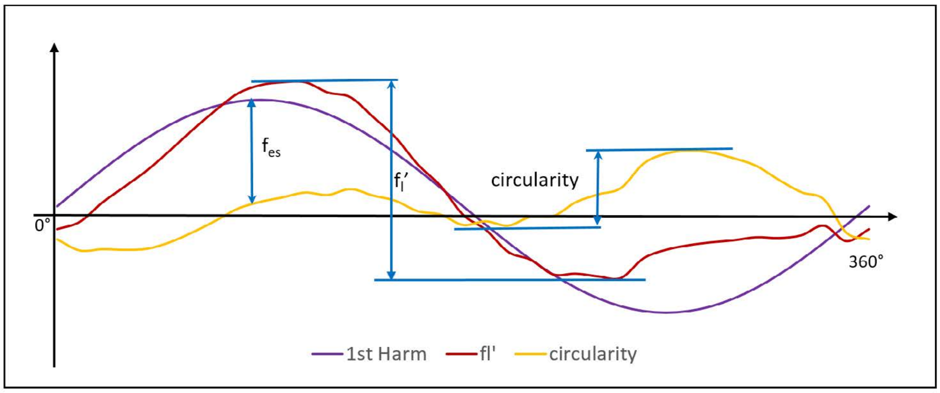



Figure 12 – Representation of the $f_l$', circularity and $f_e$ arrays

## DIMENSIONAL MEASURES

Single Flank gauges can also be used to perform dimensional measurements, such as Diameter over Balls (DoB or OBD), tooth thickness (FTT) or Wildhaber measurements. Since the single flank roller checker operates with a fixed center distance between the two spindles, any variation in the dimensions of the workpiece will be reflected as a changes in measured backlash. Specifically, as the DoB value (FTT or Wildhaber) of the measured wheel increases, the measured backlash decreases - and vice versa. These measurements require the use of a setting master, and are typically expressed as average values.

It is important to note, however, that these measurements are derived from backlash measurement between meshing teeth and, strictly speaking, are not directly comparable to those obtained in the metrological room. Nevertheless, the calculated dimensional measurements are able to provide very good indications of variations in gear machining and are therefore often included in the list of measurements to be monitored for production quality control. Figure 13 shows the correlation between Backlash arraysand DoB variations.

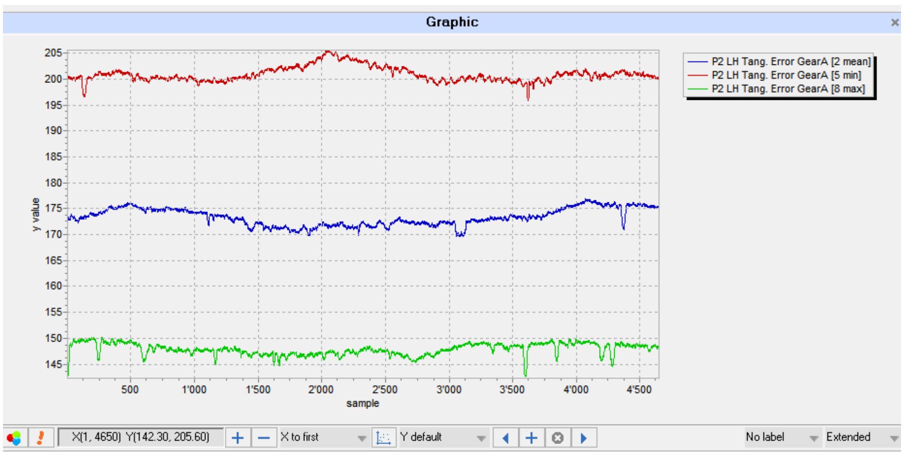



**Figure 13** - Backlash arrays acquired on part with different DoB values
(min DoB = red line, medium DoB = blue line, max DoB = green line)

## TRANSMISSION ERROR FFT ANALYSIS

A frequency analysis can be performed on the transmission error signals obtained from both flanks of the gear - Drive and Coast (Figure 14) - to decompose the signal into its harmonic components. The first harmonic typically corresponds to the rotational frequency of the workpiece around its axis, while the subsequent harmonics provide indications of the more complex vibrational characteristics of the system. This analysis enable a predictive assessment of the noise the gear wheel may generate during real operation. As the required resolution increases, i.e when distinguishing between closely spaced harmonics, the number of rotations that the measurement system must acquire to achieve the necessary accuracy in spectral decomposition, increases.

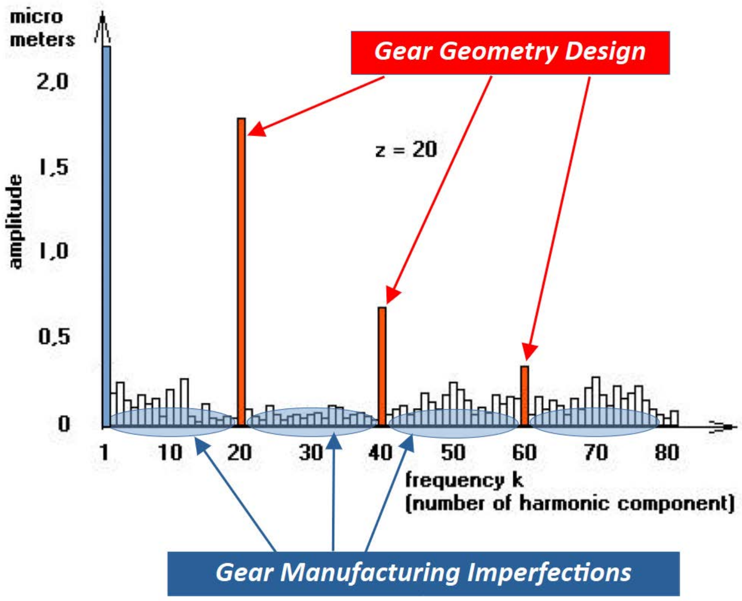



Figure 14 - Example of frequency analysis

Each harmonic is characterized by two key parameters: amplitude and frequency. By analyzing the position of the harmonics in the frequency spectrum, it is possible to recognize the presence of specific manufacturing defects, such as pitch errors, eccentricities, misalignments, or unevenness in the tooth profile. The main limitation of single flank testing lies in the low-test speeds and limited sampling resolution of the rotary encoders. These constraints significantly reduce single flank's ability to detect small amplitude (sub-micron) defects, especially those occurring at high frequencies.

## NVH GEAR TEST WITH TORSIONAL ACCELEROMETER

To overcome the limitations of Single Flank technology, in accurately detecting high-frequency harmonic components, an alternative approach can be adopted: the NVH test (Noise, Vibration, and Harshness) based on the use of a torsional accelerometer (Figure 15). The two methods share numerous characteristics in the general mechanical layout and from a functional point of view, so much so that they can often be integrated into the same machine. The key difference lies in the nature of the measured quantity:

- The Single Flank measures angular deviations, expressed in µrad, by means of rotary encoders.
- The NVH test instead measures torsional accelerations, expressed in rad/s^2 or, more commonly, in dB.

The NVH test is performed at high rotational speed (> 400 rpm), with an applied torque ranging from the minimum necessary to mantain flank contact up to the maximum allowed by the clamping device. The measurement requires a significant number of workpiece revolutions but, due to the high rotational speed, the cycle time remains very short.

The energy introduced into the system by the high speed enables even small defects to produce significant, and therefore detectable vibrations, making the NVH test particularly effective in identifying subtle anomalies.

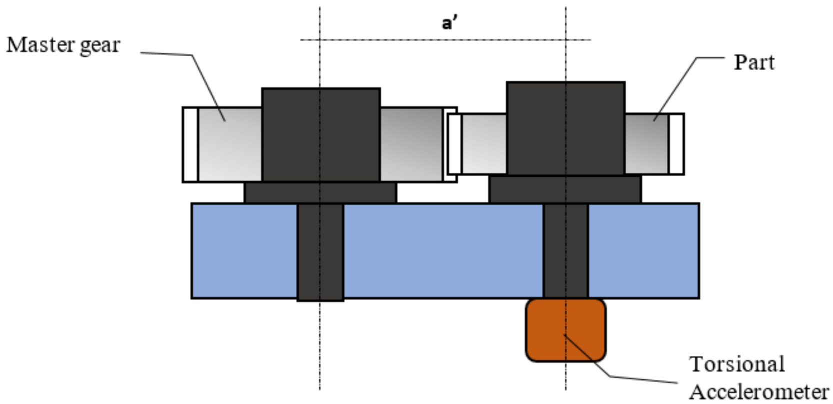



*Figure 15 – NVH concept scheme*

**Figure** 15 – NVH concept scheme

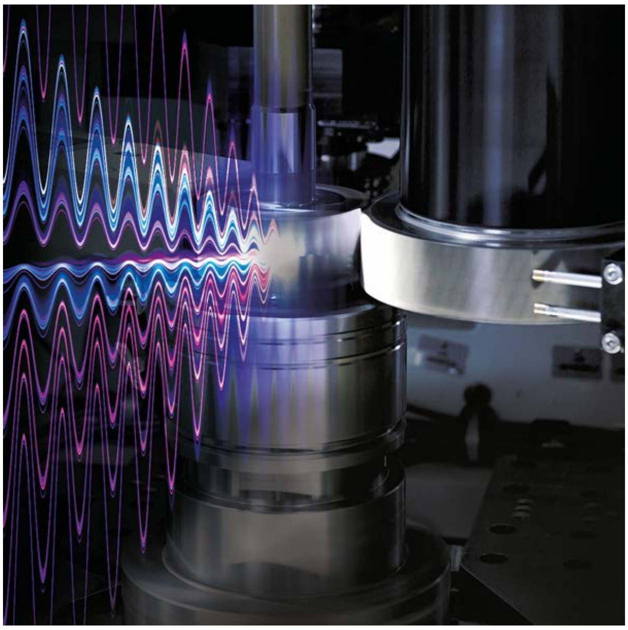


**Figure 16** – MARPOSS NVH G-EAR TEST

Furthermore, the NVH test can be performed in order-tracking mode, where the measured gear is not tested at constant speed but instead during a controlled speed ramp. As the speed increases, harmonic components are recorded, and it is possible to perform a tracking of each feature defined in the spectrogram such as side bands, order groups, etc..

Alternatively, shorter speed ramps can be analyzed using the speed band evaluation function. This approach makes it possible to evaluate noise sources by focusing the analysis on the critical intervals of transmission operation.

Speed ramp measurements are commonly used for end-of-line (EOL) checks on complete drives, helping to identify critical rotational speeds. When applied to individual gears, this type of NVH improve improves the signal-to-noise ratio, making certain defects stand out more clearly from the background noise. At low speeds, low order harmonics (< H1) are clearly visible in addition to the H1 order as well as multiples and their side bands. High speeds are accompanied by higher energies introduced into the meshing, allowing micro defects that would otherwise be barely visible to be revealed.

It's important to stress that the signal collected during the NVH test represents the overall dynamic interaction between the two meshing wheels, it is not immediate to isolate the contribution of the individual component. To correctly attribute defects to the wheel under test, the difference between the revolution periods of the two gears is used. When the gear ratio is different from 1, the collected signal is segmented into packets corresponding to a complete period of the element being measured. By averaging these cycles, it is possible to suppress the contribution of the other gear and reduce external noise, resulting in a more accurate characterization of the test piece alone (see Figure 17).

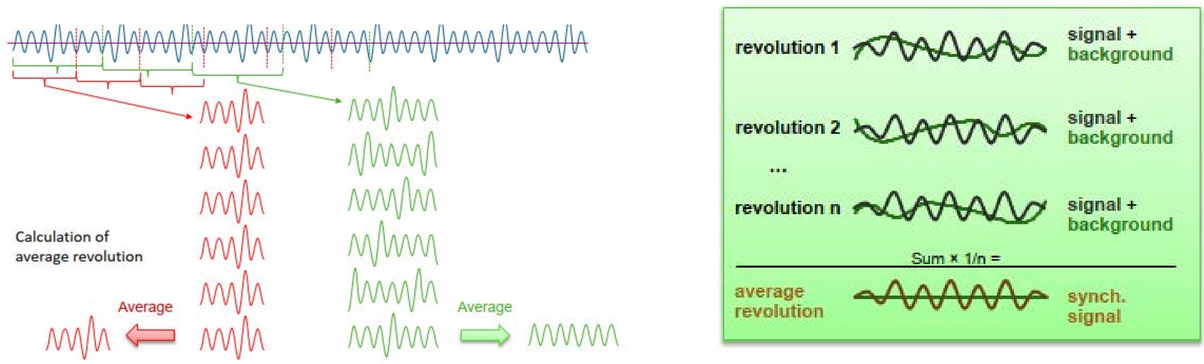





**Figure 17** – Graphical representation of the average revolution calculation method

Compared to SBN (Structure Born Noise) technology, this NVH approach is less affected by the gauge's own resonances, making the result more robust and repeatable.

## SPECTRUM ANALYSIS

The time signal collected with the torsional accelerometer during the test is analyzed through the Fast Fourier Transform to define the gear spectrum, thus obtaining a useful frequency representation to identify the main vibrational components.

From the spectrogram, the amplitude in dB of the harmonics of interest is collected.In Figure 18, an example of gear spectrum is shown.

Typical values calculated from the time signal spectrum are: overall energy (RMS) also evaluated on subgroups of harmonics & the highest value, defined as Peak.

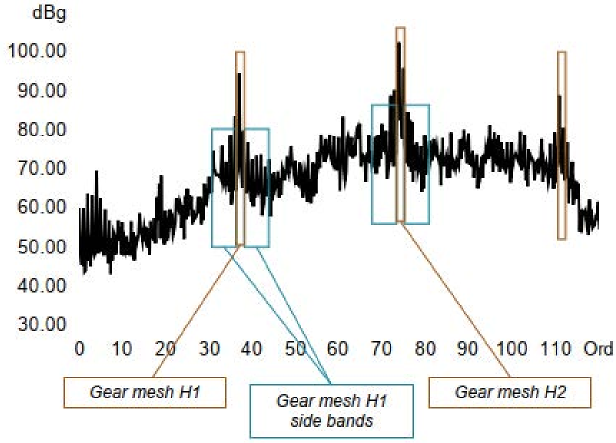





**Figure 18** – Typical EV gear spectrogram

Based on the position of a harmonic within the frequency range, the following groups can be defined:

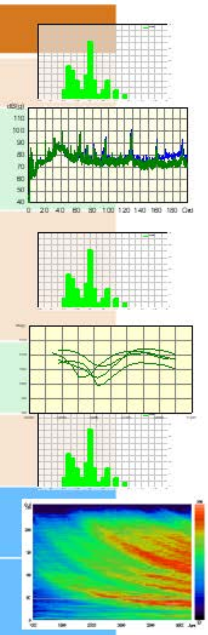
- Fundamental rotation harmonic UPR = 1. Due to a misalignment of the gear wheel generating eccentricity. Typically, due to incorrect mounting of the workpiece on the machine tool or the wheel on the gear during measurement.

- Harmonics between 2 and Z-1. Can indicate pitch and profile errors.
- Meshing frequencies. The main component of the spectrum after eccentricity is the harmonic order equal to the number of teeth and its integer multiples. In the case of wheels without profile modifications, it can easily indicate an error in the pressure angle or an error in the actual tooth pitch. In the case of design-modified wheels, these frequency components are expected.
- Side bands. Other harmonics of detectable amplitude appear around the meshing frequencies. These are frequency modulations of the meshing harmonics caused by the presence of large low-frequency harmonics such as run-out and circularity of the reference diameter.
- Ghost orders. A generic term used to indicate any harmonic that occurs with non-negligible amplitude and frequency that is not mathematically related to typical wheel harmonics and their multiples.

In the light of the above, NVH analyses can be performed with different operating modes, depending on the specific control objective. The following table summarizes the different results of NVH analyses depending on the test mode (spectrum or order tracking). The results are presented in different forms: single values, vectors or multi-dimensional objects such as spectrograms.

NVH analysis results can take the form of single values, vectors or multi-dimensional objects such as spectrograms. See the following table.

| Source | Examples | Result Types |
|---|---|---|
| Time Signals | RMS, Crest, Peak | Single value |
| Spectra | Order spectra (synchronous and mix), fixed frequency spectra, Deviation spectra | Curve (spectrum) |
| Single orders taken from spectrum (or sums of orders, band sums) | Gear mesh order value H1, side bands, order sum Hx, specifically selected orders | Single value |
| Orders tracked over ramp | Gear mesh order track, RMS track | Curve (track) |
| Values computed from tracks | Speed bands, difference to reference polygon | Single Values |
| Spectra tracked over ramp | Spectrogram | Spectrogram |
| Short Time and Modulation analysis | Short time spectrogram, Modulation spectrogram, modulation content | Spectrogram → Spectrum / single value |



© Hottinger Brüel & Kjaer GmbH (Discom by HBK)

**Table 1** – NVH results table

## THE SELF-LEARNING PROCESS

For single flank gear measurements, it is possible to unambiguously define the tolerances to be applied, following international standards, as they are defined from design data such as module, number of teeth, and quality grade (DIN, ISO). On the other hand, as seen above, NVH measurements are are inherently influenced by the characteristics of the measuring system itself. Noise sources and machine resonances give a unique spectral 'signature' to the results. As a consequence, the raw

NVH measurement data cannot cannot immediately determine whether a gear is conforming or non-conforming.. To address this, statistical learning of the production process must be performed. The gear manufacturer provides a set, even limited to only 5 initial samples of parts considered “good” by previous measurements in the metrology room (GMM), EOL, or verified on test vehicles. The parts are measured on NVH, and the average values and standard deviations of all required measurements are calculated and used by the software to automatically calculate acceptability thresholds, so that parts “less noisy” than the threshold are considered good. The self-learning process proceeds automatically until a number of approximately 200 items are reached, making the calculated limit curve more robust.

The automatic process can be further refined manually, adjusting the thresholds. The entire process can be repeated should significant changes in the production process result in variations in the average spectrum of the parts. It is also strongly recommended to include known defective (rejected) parts during this process, as they help to sharpen the distinction between acceptable and non-conforming components, thereby improving the accuracy of the limit curve.

## MEASURES CORRELATION AND INTERCORRELATION

In this chapter, we will address the topic of correlation between the results obtained from Single Flank, NVH and related reference CMM applications. Additionally, we will consider intercorrelation, which refers to the comparison of results obtained from twin Single Flank or twin NVH setups. By definition, correlation between measuring systems can be investigated when there is similarity in the measuring principles, and the acquired quantities are comparable. In traditional dimensional measurements, this function is performed by comparing the results obtained from shop floor measuring systems with those from coordinate measuring machines (CMMs) in the metrology room.

### SINGLE FLANK RESULTS

Like all industrial measurement systems, the main objective of single flank measurement is to intercept non-conforming components before they continue in the production flow. Unlike the SF test, CMM measurement employs small-diameter spherical probes that selectively explore the flanks of the teeth and calibrated balls that are positioned in the recesses corresponding to the primitive diameter. This allows the different elementary errors to be isolated and measured individually, but does not return dynamic or functional information related to actual meshing. Figure 19 and Figure 20 show how a metrology room certificate can separate and evaluate elementary errors.

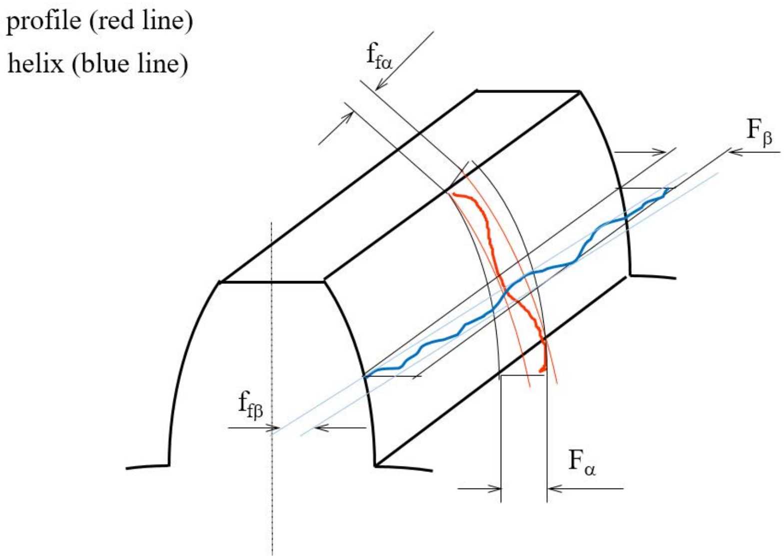



**Figure 19** – Exemplification of elementary errors of teeth flanks: Profile (red line) & Helix (blue line)

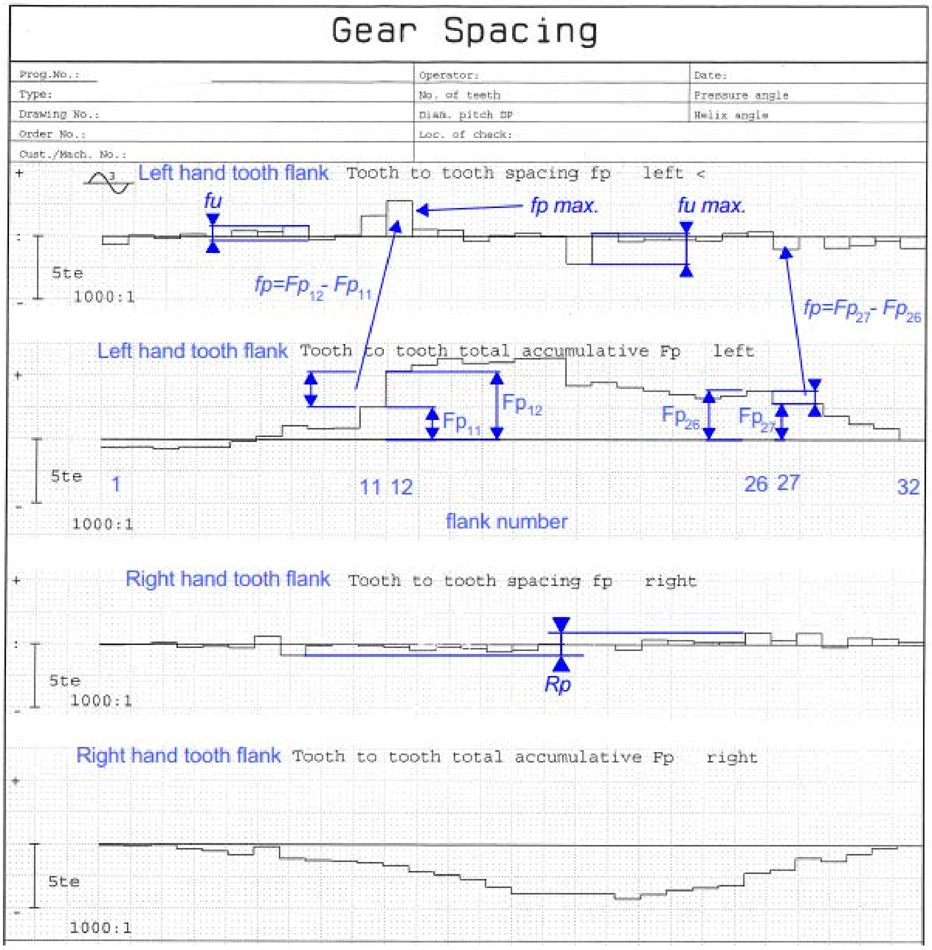



**Figure 20** - Metrology room certificate with details of tooth-to-tooth and cumulative pitch measurements.

In the case of the Single Flank test, the precondition for a standard correlation analysis with CMMs is not met. To emphasize this underlying difference in methodology, the international standards [1] and [2] indicate the SF's features with specific names, symbols, subscripts or with superscripts, to avoid misunderstandings (Fp' is different from Fp). The flipside of this argument is that a coordinate measuring machine cannot replicate the dynamic contact between master wheel and workpiece wheel, nor can it return the functional values obtained from a real rolling test.

Unlike a profile measuring machine, SF results are two arrays representing the overall effect of the transmission error detected during meshing between the test piece and the master wheel. It is no coincidence that the method is known as tangential composite action. This type of measurement returns global information on all defects in the workpiece - such as profile, pitch, helix and runout errors - as "seen" by the rolling master. The measured quantities only allow a partial distinction between the sources of the defects, but do not allow a deterministic attribution to individual elementary defects like Figure 20 exemplifies.

It's worth mentioning that the Single Flank test allows for the unambiguous definition of tolerances, as it is based on international standards and design parameters such as module, number of teeth and quality grade. The quality grade also represents the overall output of measurements performed in the metrology room. Although not directly correlated, both methodologies (Single Flank and CMM) contribute to the quality classification of the gear. In general, it can be stated that gears with low runout values, small pitch and profile errors measured in the metrology room will tend to show low values in the SF test as well; however, there is no direct and deterministic correspondence between the two sets of results.

The reliability of the data obtained with a single-flank gear depends heavily on the quality of the setup, which includes: correct assembly, precise alignment, high quality rolling master, proper programming and accurate testing. Ultimately, the only verifiable parameter is the repeatability of the system, which improves significantly with optimized operating conditions. A good set-up also favors qualitative consistency between measurements made in the metrology room and those obtained on the test bench. If an interrelation between several identical measuring benches is to be carried out, the most critical element to be checked is the parallelism between the axes of the master wheel and the workpiece wheel. Excessive misalignments result in different contact between the teeth and therefore results that are not comparable between the various benches. Consistency of results therefore depends on both the mechanics of the twin applications and the quality and repeatability of the rolling master used.

## NVH RESULTS

The scope of the NVH test is to intercept defective components before they reach the End Of Line (EOL) stage, where the entire transmission is tested as a whole. Detecting non-conformity at this late stage means that the transmission must be disassembled, the defective part identified and replaced with a significant impact in terms of time and operating costs. The main difference from SF testing lies in the statistical self-learning process that characterizes NVH systems. During this initial phase, it is the customer who provides the reference samples, i.e. parts already validated as compliant by either GMM measurements, EOL tests, or both. These components form the statistical learning baseline of the system, which records the typical spectral signature of its acoustic and vibrational behavior. Once this baseline is acquired, the NVH system is able to identify anomalous deviations in subsequent pieces by comparing them with the historical database of good samples. In this way, potentially defective parts can be quickly identified on the basis of localized spectral anomalies on specific harmonics.

An application example highlights the effectiveness of the method: two parts declared as rejects by EOL were measured using GMM, whose software processed the theoretical spectrum of the expected transmission error based on the detected geometries. Figure 21 shows the detail of the room certificate, where an anomalous peak at harmonic 117 is most evident on the coast side.

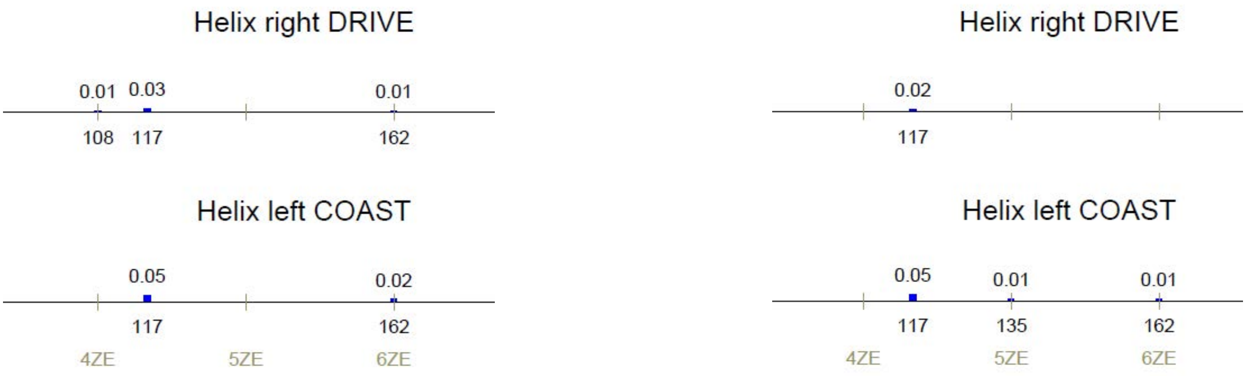



**Figure 21** – Metrology room certificate with theoretical spectrum processing

Subsequently, the two parts were tested on the NVH bench: the results confirmed the non-conformity by showing an anomalous peak on the expected harmonic, with the two components clearly identified as rejects. Figure 22 shows the spectra of various gears measured, and in green, the two reject gears are highlighted, characterized by an amplitude of harmonic 117 above the threshold on the coast flank.

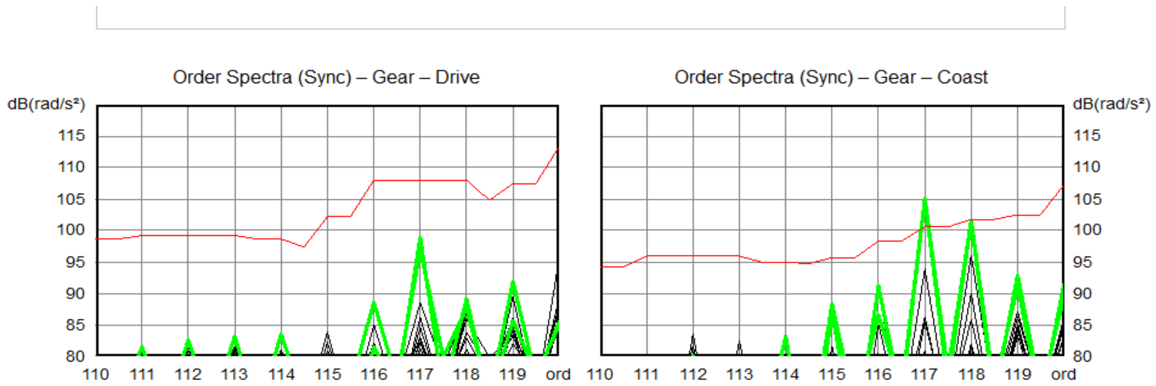



**Figure 22** – NVH test result of the two noisy gears

## CONCLUSIONS

Profile and lead modifications to the tooth flanks are unavoidable to allow good contact between the teeth, even in presence of elastic flexing (teeth and shafts) and misalignment (of the shafts) due to production tolerances and deformations under the load. Without modifications, the gear can incur excessively high specific pressures that would compromise the life and reliability of the transmission. It is true that these modifications generate a non-zero transmission error, but it is a matter of making a trade-off between the noise behavior of a wheel and its load-bearing capacity.

Tooth geometry checks (GMMs) can give indications on how to correct the production process and can give some indication on the possible spectral content of the transmission error of the wheel. However, these checks are slow and not suitable for production environments.

SF & NVH rolling tests are specifically designed to measure transmission error and are very useful in determining whether or not a wheel will be noisy once it is put into transmission operation. Since the results are affected by the superposition of elementary defects, they give poorer indications of how they will affect the process, but can quickly detect variations in production.

## REFERENCES


| | |
|---|---|
| [1] | ISO/TR 10064-1:2019 Code of inspection practice – Part 1: *Measurement of cylindrical gear tooth flanks.* |
| [2] | ISO 1328-1:2013 Cylindrical gears – ISO system of flank tolerance classifications – Part 1: *Definition and allowable values of deviations relevant to flank of gear teeth*. |
| [3] | D. Marano, L. Pascale, J. Langhart, S. Ebrahimi, Y.Giese, «*NVH Analysis and Simulation of Automotive E-axels*», **Gear Technology**, January/February 2021, pp 58-70 |
| [4] | H. Müller, C. Gorgels, «Aspects of Gear Noise, Quality, and Manufacturing Technologies for Electromobility», **Gear Technology**, January/February 2023, pp 58-63. |
| [5] | M. Pueo, J.Santolaria, R. Acero, A. Gracia, «*A review of tangential composite and radial composite gear inspection*», **Precision Engineering**, Volume 50, October 2017, pp 522-537 |
| [6] | Dr.-Eng. Ulrich Kissling, «*Effects of Profile Corrections on Peak-to-Peak Transmission Error*», **Gear Technology**, July 2010, pp 52-61 |
| [7] | Dr. A. Türich, «Producing Profile and Lead Modifications in Threaded Wheel and Profile Grinding», **Gear Technology**, January/February 2010, pp 54-62 |
| [8] | Owen Harris, Paul Langlois and Andy Gale, «*Electric Vehicle Whine Noise — Gear Blank Tuning as an Optimization Option*», **Gear Technology**, March/April 2019, pp 64-73 |
| [9] | J. Bihr, Dr. M. Heider, Dr. M. Otto, Prof. K. Stahl, T. Kume and M. Kato, «*Gear Noise Prediction in Automotive Transmissions*», **Gear Technology**, August 2015, pp 66-70 |
| [10] | Matthew Jaster, «Shake, Rattle and Roll Software Providers Examine the Dynamic Behavior of Gear Noise», **Gear Technology**, June 2018, pp 26-30 |
| [11] | Hottinger Brüel & Kjaer GmbH (Discom by HBK), *«DISCOM Rotas Training (English)»*, **DISCOM** |

## PARTNER

Marposs was founded in 1952 and Mr. Stefano Possati is the President of the Group; it provides shop-floor solutions for measurement, inspection and testing in the production environment.

Leading supplier to the main automotive and aerospace manufacturers, Marposs is widening its offer towards the biomedical industry, by combining measurement accuracy and compliance with standards. It includes dimensional and functional controls as well as leak, flow, burst tests customized to the various types of biomedical components and their machining process. Thanks to this large portfolio, Marposs fulfills user-specific requirements in terms of measuring methods (tactile vs contacless) of repetability, of robustness within machine tools, by a complete project engineering from the use case to training and maintenance.

Specifically in the field of orthopedic manufacturing, in addition to the automated control system for implants, Marposs performs measurements of diameters, roughness, small-size surface defects, and angles of prosthetic components (hip, knee, shoulder) by laser micrometers, chromatic confocal senors, and pneumatic air gauges sensors as well as in/post-process contact gauging of hip joints within grinding, polishing and turning machines.

Marposs Group employs 3500 people around the world and is present in 34 countries with more than 80 sales offices.

MARPOSS