DIN Q6 Meets DIN Q10—the Need for Modern Internal Gear Production

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Challenge—Design Space and NVH

A meaningful discussion about noise is quite difficult because the impression of "noise" is quite subjective. Everybody has a lifetime experience with sound / noise and sees themselves as an expert. I carried out such a test with my family and the results can be seen in Figure 1. The exterior noise of an airplane makes just my son "happy," whereas exterior and interior engine V8 noise makes *me* happy. The only consensus is—"silence is golden."

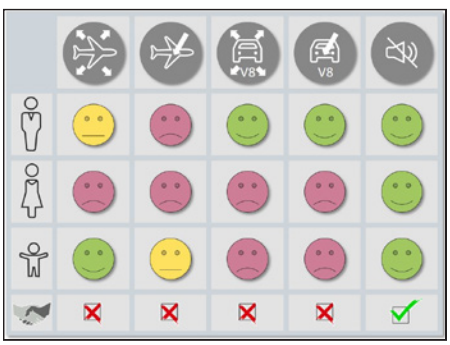

Figure 1 Subjective feeling of noise.

E-cars are by nature on a lower NVH-level, due to the loss of masking ICE noise and to other components getting in the focus, e.g.—e-transmissions, power electronics, e-motors. NVH activities are necessary because these cars are strongly picking up market volume. In the year 2030 it is forecasted to have a split of 30% ICE—40% hybrid—30 % e-vehicles.

Transmission engineers will do their best in lowering NVH level, but with the increase of quality, costs will also go up. This "trilemma" must be broken by a compromise between structure-borne noise, airborne noise and costs.

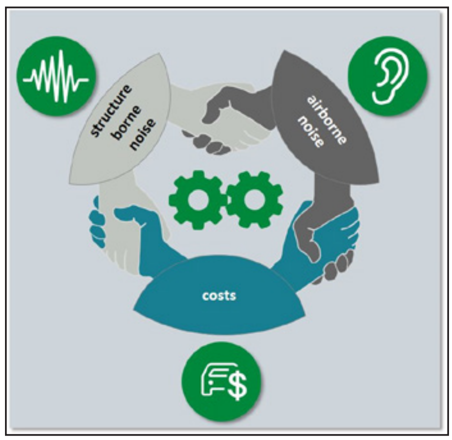

Figure 3 Trilemma gear design.

Conclusion—Integral Understanding Required

"DIN Q6-meets-DIN Q10" is probably not a desirable choice in quality to apply acoustic modification on a planet gear (Fig. 4). DIN Q6 reflects the current feasibility for the mass production quality level of planets and DIN Q10 was in the past a satisfying level for internal gears. In order to boost the internal gear quality to a similar level as external gears, several activities had to occur; it was essential to go into every production step—from raw material to the final parts—including feasibilities and their interaction. QA inspection methods had to be developed to do precise predictions on an expected NVH level.

It proved that a very high knowledge throughout the entire production is mandatory.

Gear Quality—Basics of Quality Classes

Transmission gear noise is influenced by several failures as geometrical deviations, gear tolerances, surface roughness or surface mapping. This report will focus on the gear tolerances.

Noise is always linked with dynamics, meaning that there must be a kind of speed which results in alternations, e.g.—due to driving style, imperfection of parts or alternation of power input. A gear at the input shaft faces speeds up to 20,000 rpm and the accumulated number of revolutions during service life pile up to 1 billion revolutions. The

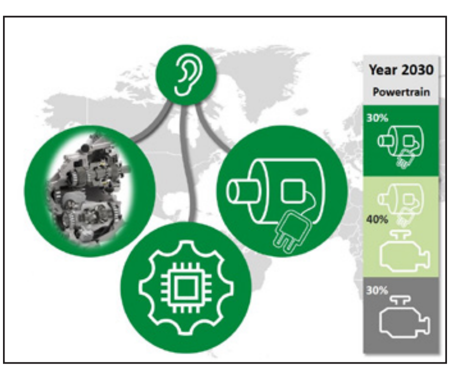

Figure 2 Market development 2030.

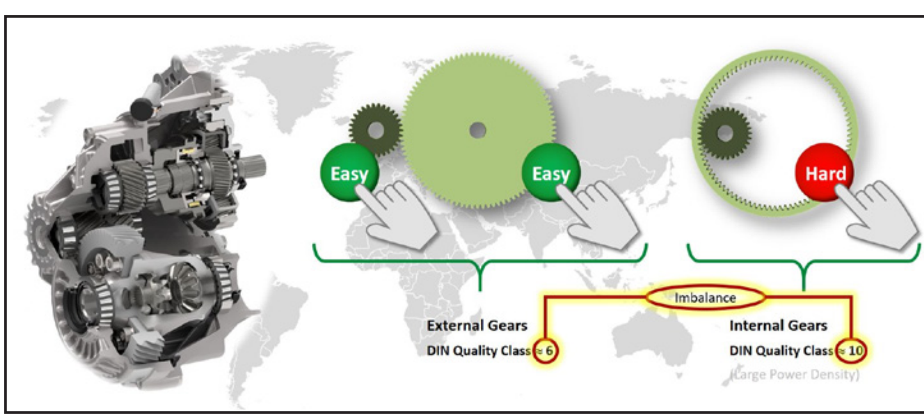

Figure 4 Imbalance of quality.

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circumferential speed goes up to 50 m/s. The differential case/final drive gear has a speed of up to 2 rpm and the accumulated number of revolutions is around 100 million. This number equals a mileage of about 200,000 to 250,000 km. The speed inside of a differential is much lower, and if no type is losing contact to street, the delta speed between both output sides is less than 50 rpm. In case of µ-split test (icy/snowy road), it can go up to 500 rpm.

Rotational speed is linked with a recommended quality level of gears. High speed requires lower DIN Q-classes (less deviations, fine quality) so that the incoming gear should be, for example, in DIN Q5-to-Q6. Due to gear ratio and lower rotational speed, the final drive is sufficiently designed at DIN Q7. Differential gears due to static or low frequency meshing come up with higher DIN Q-classes (more deviations, coarse quality).

The link between the different tolerance classes is done by a geometrical series (Fig. 8); this definition helps to quantify the quality independently from size, width, module and helix angle.

It is easier when the number of the geometrical series is transferred to an x-y plot; the plot shows that an elevation of two quality classes results in doubling the tolerance; a difference of 4 quality classes quadruple the tolerance.

The diagram (Fig. 9) shows impressively the difference between a DIN-Q6 planet with a DIN-Q10 ring gear in each failure mode.

The imbalance is large for all gear failures and is usually between factor 4 and 5.

Switching the ring gear to quality DIN Q8 results in a much better balancing for the failure modes, so that now the given deviations for the ring gear are only between 2 and 2.5 times higher than the deviations of the planet gear.

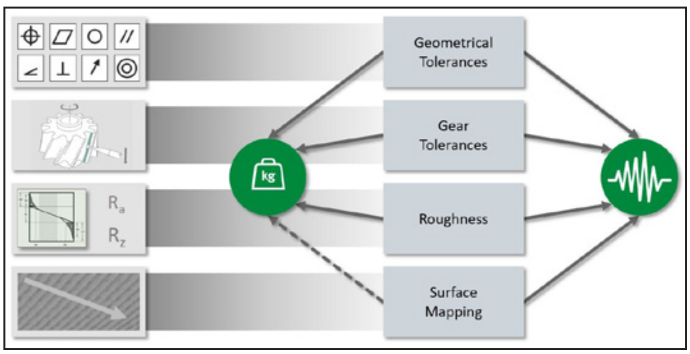

Figure 5 **Origin of noise.**

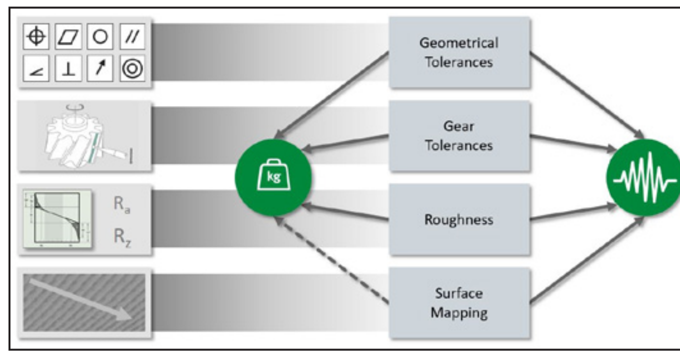

Figure 6 **Transmission speed and cumulated revolutions.**

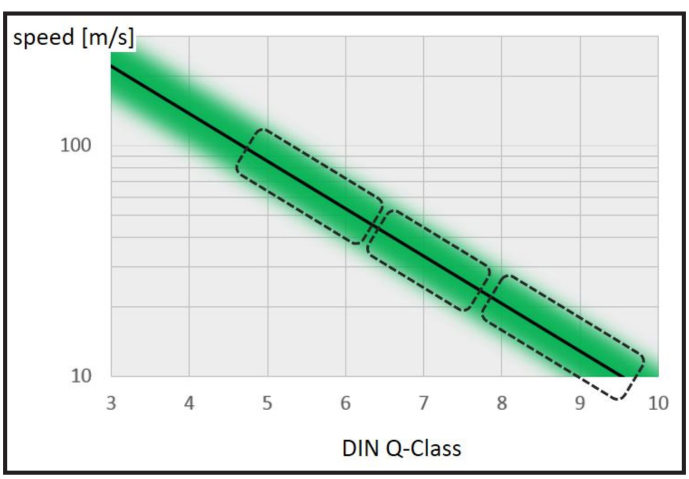

Figure 7 **Speed and quality classes.**

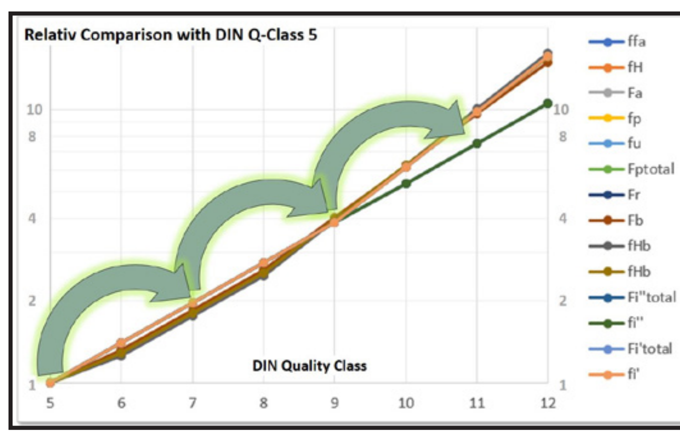

Figure 8 **Relative comparison of quality classes.**

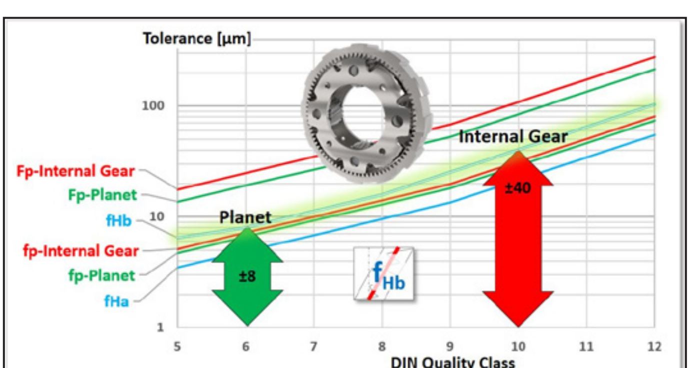

Figure 9 **Lead angle error for Q6 planet and Q10 internal gear.**

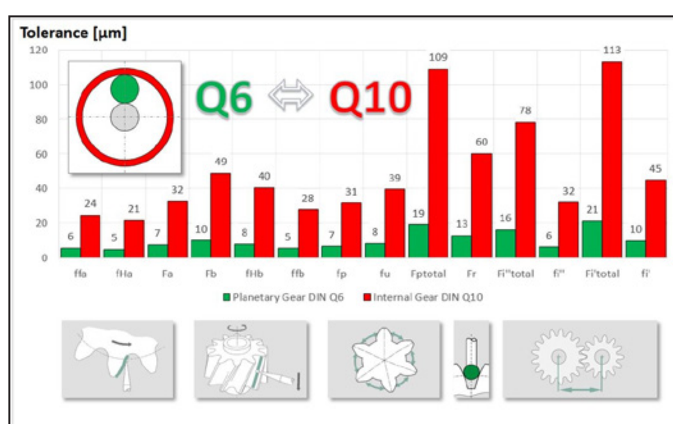

Figure 10 **Gear error Q6 and Q10.**

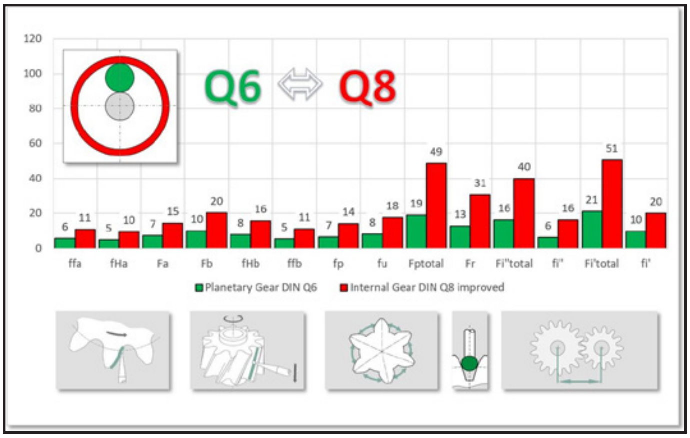

Figure 11 Gear error Q6 and Q8.

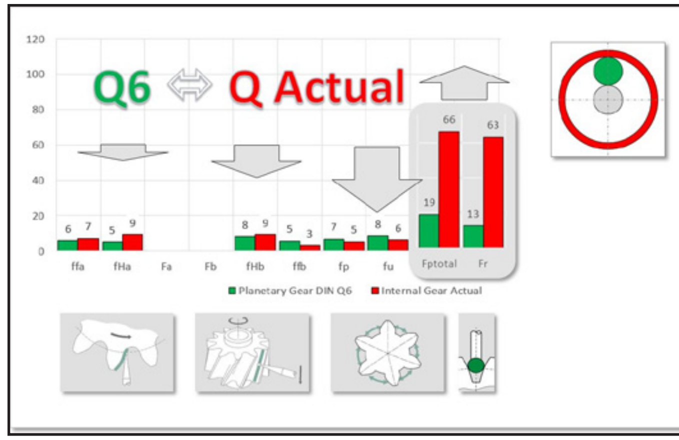

Figure 12 Real internal gear quality.

DIN Q8 for ring gears requires a highly sophisticated production process with robust quality monitoring and good stability after tool reworking operations.

With high-end machining processes, the quality level can be further enhanced. This can be seen especially in the single pitch error *fp*. On the negative side there is a larger total pitch error for *Fp* and *Fr*.

Higher deviations/DIN-Q classes for ring gears derive from the gear geometry itself affecting machining / heat treatment/clamping etc. This is not surprising because a DIN-quality system does not distinguish between external and internal gears. External gears usually come with a more rigid structure or part design, whereas the internal gears are designed as thin rings with high elasticity and large internal diameter due to gearbox design with high power density. The raw material, heat treatment, gear outside diameter and clamping jigs have higher impact on total errors as *Fr*, *Fp* or OBD (on-board diagnostics) span for internal gears with thin rims. But, in general, increased deviations for *Fr*, *Fp* or OBD span do not have to directly result in increased gear mesh excitation and noise.

Different errors of internal gears can be improved by optimizing the machining process, e.g. — tool optimization; proper machine type and machine setting; optimal raw part before machining (residual stresses due to forging); clamping jig; heat treatment (distortions), etc. (Fig. 13).

The data in Figure 12 now looks more satisfying, but a general gear inspection report does not provide a clear link to NVH topics. Acoustic testing of the whole transmission system in the car (Fig. 14) (anechoic chamber/dedicated measuring equipment) must be done with respect to correlation between NVH behavior of the car and the geometric deviations/gear quality of each geared part. The transfer path internal gear, planetary gear set transmission, axle transmission assembly, car and finally to driver's ear is quite long, and testing is time- and cost-consuming. Inspecting each geared part by 3-D coordinate measuring is desirable for every gear expert, but horrible due to costs and effort in gear measurement. Cost-effective measurement methods like double or single flank inspection are in focus when it comes to create correlations between gear quality and NVH behavior of the whole system.

These simple inspection methods then can be used to prevent added-value in case of insufficient NVH quality. Schaeffler is a large global player in automotive engineering, with a lot of experience in bearing quality inspections. Gear quality inspection is in this case highly inspired by methods used for bearings.

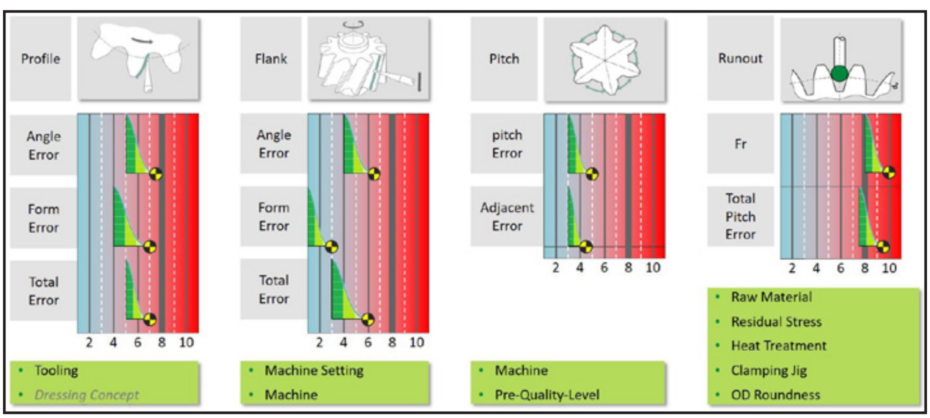

Figure 13 Options to tune quality.

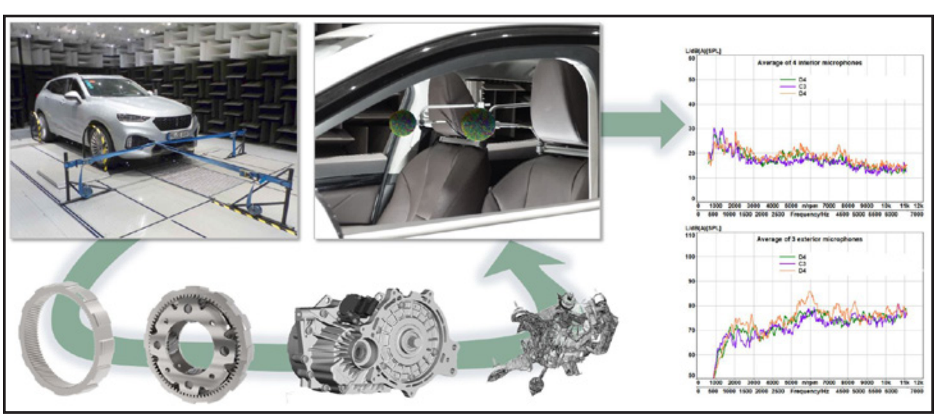

Figure 14 NVH analysis.

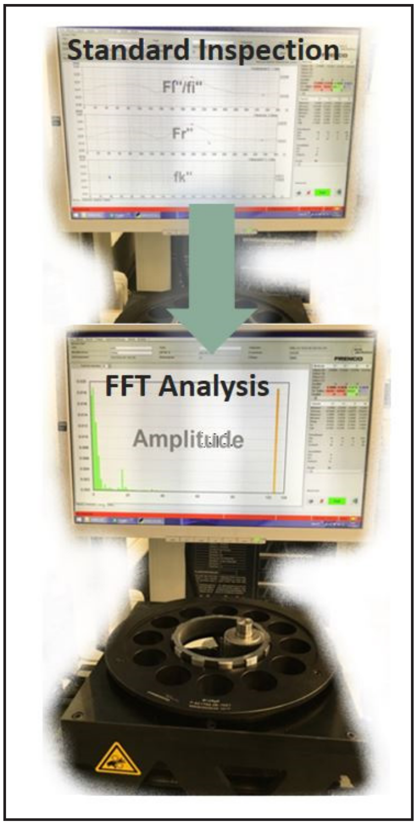

Figure 15 Double flank inspection.

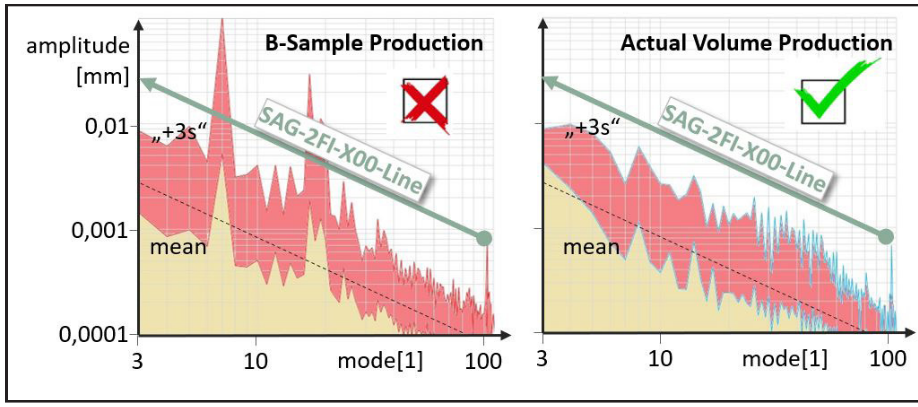

Figure 16 Good and poor internal gear quality.

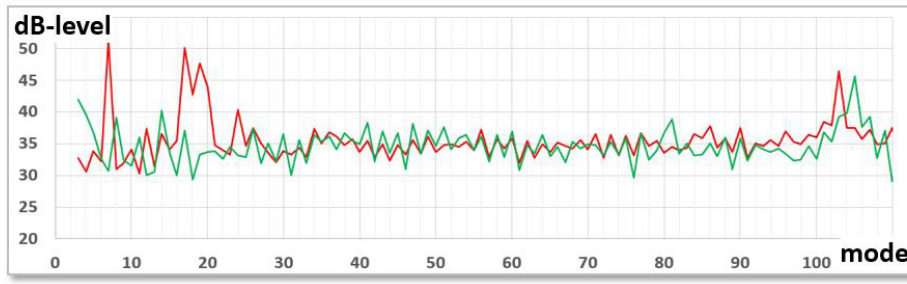

Figure 17 dB noise level after double flank inspection.

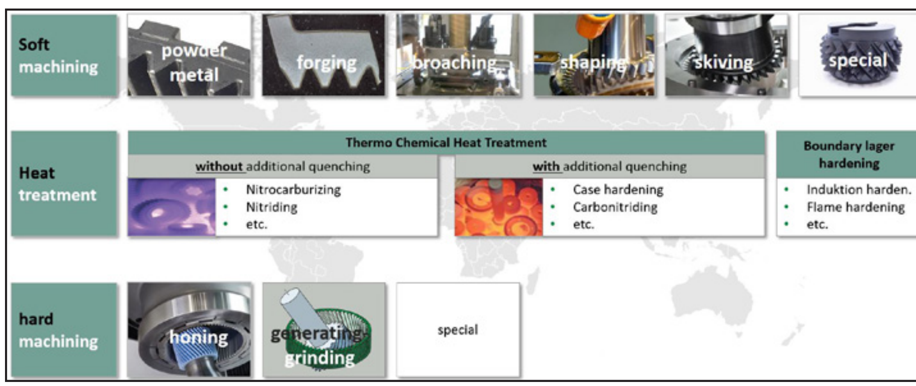

Figure 18 Comprehensive understanding.

In some points bearings and gears are quite similar — especially when getting to the point of inspecting waviness effects. Here Schaeffler found large similarity between transmission error, accelerations and noise.

The double flank inspection (Fig. 15) is a standard device to inspect gear quality. It is, compared to 3-D gear inspection machines and single flank inspector, inexpensive, fast and robust; the key point is the FFT analysis. By using raw data of the double flank inspection for a post-processing transferring, time-based signals into frequency-based deviation analysis on each part, it is easy to distinguish poor and good gear production and to have a much deeper look into machine properties (Fig. 16). Deviations or resonance effects, e.g. — during the machining process — will directly lead to periodic deviations in quality which will be directly highlighted to the quality inspector by FFT analysis. On the left side, there is a manufacturing with production difficulties in mode 7 and between 16 and 20; parts are exceeding the first design level NVH line "SAG-2FI-X00." The right side shows an optimized production which stays everywhere below the acceptance criteria.

An additional view was created to support NVH criticality rating. Several tests proved that this method has good correlation with cost- and time-consuming NVH testing in an anechoic chamber. Schaeffler is now able to express part NVH severity before it goes into additional value-add production steps.

Manufacturing

There are many methods and processes for manufacturing of internal gears, and there is no royal road to the best "no NVH" gear. Several developments over the last years revealed that surprisingly many processes and process combinations can pave the road to the best compromise (cost ⇔ NVH). The saying "Do the right thing, right!" are indeed words of wisdom. It goes without saying that the "compromise" is very much driven by the short development time in e-mobility and still the small and medium volume of parts.

NVH is one of the results in overall system performance with lots of influences like transfer path, structural resonance behavior and noise excitation. Regarding the gear mesh excitation for some parameters in gear geometry, there is a trace to its source in soft machining or even before (Fig. 18). A comprehensive understanding is the road to success. The comprehensive understanding requires a data mining concept (Fig. 19) which gathers all the information in the parts life cycle, e.g. — data of the raw material, information of the forging process, heat treatment parameters, machining information, measurement results of gear geometry after each process step in gear production and creates the ability of comparing them to NVH behavior of the overall system (car, gearbox on test rig etc.). Significant parameters — or even groups of parameters — can be highlighted and optimized due to better NVH performance. On the other hand, robust parameter groups can be used to optimize gear machining and production processes due to costs and efficiency.

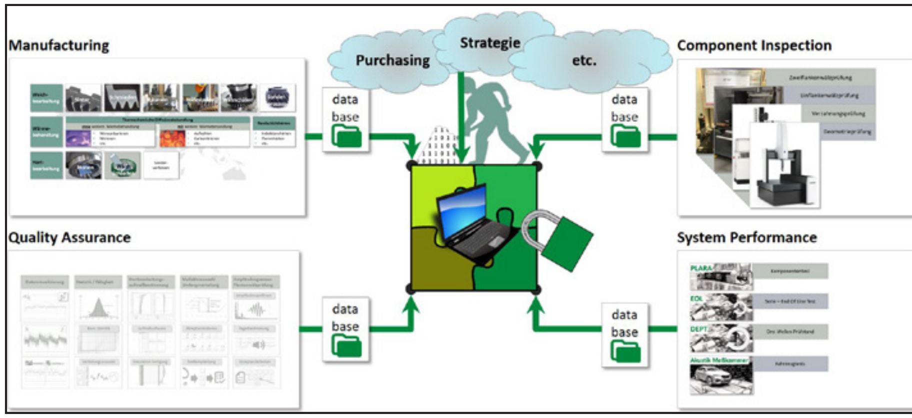

Figure 19 Data mining as one key to optimize NVH and process efficiency.

For more information.

Questions or comments regarding this paper? Contact Thomas Kleiber at *kleibtom@schaeffler.com.*

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