

Review

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Review

The Impact of Manufacturing Variability on NVH in Gears and Transmissions

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Abstract

Manufacturing variability has a measurable impact on the NVH behavior of gear drives. Small deviations in tooth geometry or surface quality can increase transmission error. These effects become more pronounced in electric powertrains due to the lack of masking noise. Housing stiffness variations further shape how gear-mesh excitations are radiated as airborne sound. This review examines how common gear and housing tolerances influence NVH performance and summarizes recent advances in stochastic analysis, robust design, and measurement-driven modeling. The results show that unit-to-unit differences in gear quality and housing dynamics can shift radiated noise by several decibels. Integrating real manufacturing data, statistical tolerance assessment, and coupled structural–acoustic simulations provides a practical approach to achieving consistently quiet powertrains in series production.

Keywords: manufacturing errors; NVH; transmission error; manufacturing variability; gears; gear noise; gearbox related NVH; ghost orders

1. Introduction

Manufacturing variability in gears and gearboxes has a critical impact on Noise, Vibration, and Harshness (NVH) performance—an issue magnified in electric vehicles (EVs) where the masking noise of engines is absent. A small deviation in gear geometry or housing stiffness can bridge the gap between a silent design on paper and a noisy product in reality. **Transmission error (TE)**, defined as the deviation between actual and ideal driven gear position, is the primary indicator of gear whine noise. While designers optimize gear microgeometry (lead crowns, tip relief, etc.) to minimize TE under load, even the tiniest **manufacturing errors**—tooth spacing (pitch) errors, runout, profile form errors, surface waviness—can dramatically increase both static and dynamic TE. These unintended excitations manifest as tonal vibrations at gear mesh harmonics and as problematic “**ghost orders**” (non-integer order vibrations) that traditional analysis might not predict. In practice, achieving consistently quiet high-volume transmissions requires explicitly accounting for stochastic manufacturing variations and robust design principles, effectively building a “simulation ↔ production” bridge during development. This review examines how gear and housing manufacturing tolerances affect NVH, surveys stochastic analysis and robust design methods, and addresses the practical question: **How can we manufacture uniformly quiet gearboxes at scale?**

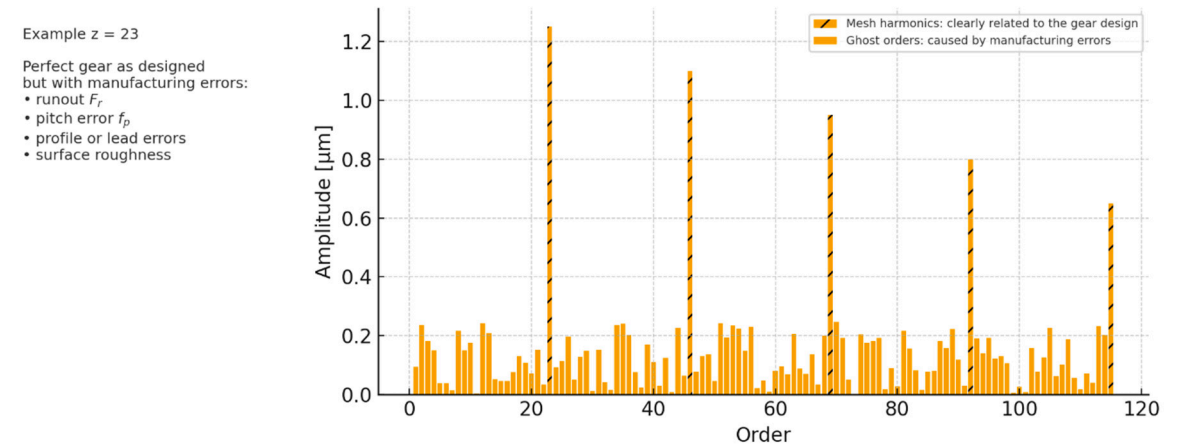
2. Gear Manufacturing Deviations and NVH Performance

Gear Geometry Tolerances: Real-world gears inevitably deviate from ideal geometry within specified **tolerances**—including pitch (spacing) error, runout (eccentricity), profile form error, lead (flank line) error, and surface finish waviness. These deviations directly increase both static and dynamic transmission error, thereby elevating noise at the gear meshing frequency orders and even introducing additional sideband frequencies (ghost tones) [1,3]. In essence, any imperfection that alters how teeth pair-wise engage will modulate the mesh stiffness or contact timing and generate

vibration. For example, even micrometer-scale pitch errors have been shown to **enlarge peak-to-peak TE and excite low-frequency “ghost” shaft-order tones** in helical gears [1]. Profile form errors or waviness on the tooth surface similarly create tiny ripples in mesh force that become audible whine or tonal “ripples” in the noise spectrum [3]. Notably, **surface waviness** (periodic undulations on the tooth flanks from grinding or honing) can be a major ghost noise contributor. Experimental studies demonstrate that waviness in the profile direction increases peak-to-peak TE by up to ~21% in a medium-quality gear (ISO Q6) [4]. Waviness in the lead (flank line) direction tends to have a smaller effect on TE (on the order of 0.2% for Q6)[4], but waviness oriented *normal* to the grinding direction (as from milling patterns) can raise TE by as much as 25%[4]. These deviations are especially detrimental for EV gears, which are held to tighter tolerances (particularly profile and lead) in order to meet the nearly “silent” noise targets[2]. In fact, **gears for electric drives must be designed and produced with much tighter profile and lead tolerances** because higher torques and speeds, combined with lack of masking noise, mean even small errors produce audible whine[2].

Ghost Orders and “Ripple” Noise: Ghost order noise refers to tonal vibrations at frequencies not corresponding to the gear mesh fundamental or its integer harmonics—essentially sidebands or unexpected orders caused by manufacturing-induced modulation. Such ghost orders are a well-known result of slight periodic errors on every tooth[5][2]. For instance, a small runout (eccentricity) in a gear will act like a once-per-rev modulation, typically generating sidebands around the mesh frequency (appearing as ± 1 order sidebands in spectrum). Similarly, a regular tooth profile ripple or pitch error might produce higher-order sidebands. Figure 1 illustrates an example order spectrum for a spur gear (23 teeth) with manufacturing errors

The red bars mark the expected mesh harmonics (23rd order and multiples), while the numerous blue bars between them are ghost orders attributable purely to errors (e.g., a prominent 59th order that is not an integer multiple of 23)[3]. In practice, ghost orders manifest as annoying “whining” tones or beats that standard smooth-gear models would not predict. They have become **strongly audible in EV transmissions**, where even a 10 dB lower gear noise can be heard by passengers[6]. Ghost order issues have driven gear manufacturers to improve inspection techniques: as one industrial NVH expert puts it, a gear perfectly within conventional tolerances may *still* produce unacceptable ghost-tone noise (the so-called “ripple phenomenon”)[2]. These ghost tones originate from micro-geometry errors in the profile or lead of gear flanks[2]. Advanced gear quality audits now include single-flank roll tests and **waviness analysis** to catch these defects. In essence, **gear tolerances and flank waviness systematically increase TE and can trigger ghost orders**, making otherwise well-designed gears noisy—a problem highlighted by both experimental tests and a comprehensive 2025 literature review[1,3].



3. Statistical and Robust Analysis of Tolerances

Because manufacturing variations are inherently statistical, deterministic “worst-case” analysis alone is insufficient to guarantee low NVH in production. Instead, researchers increasingly apply **stochastic methods (Monte Carlo simulations, reliability analyses)** to quantify how tolerances and process variations influence gear NVH metrics like TE or sound pressure. A recent review underscores that these **tolerances and uncertainties are key factors in gear NVH**, and that robust gear design must explicitly account for them[1].

One common approach is to assume each error source (e.g., pitch error, misalignment, etc.) follows a distribution (often normal) and then perform Monte Carlo sampling to see the spread in outcomes. For example, Chung et al. (2023) conducted a **Monte Carlo robustness analysis** for gear macro-geometry errors[1]. They treated tooth thickness, tip diameter, and center distance errors as independent random variables and simulated 100s of gear sets. Their results showed that even **micrometer-level shifts in macro-geometry can significantly degrade performance**. In particular, peak-to-peak static TE could **increase by over 30%** across the operating range when realistic tolerance spreads for tip diameter and center distance were considered[1]. In some Monte Carlo trials, a gear pair that had a safety factor >1 in a nominal design dropped to <1 when the stack-up of tolerances was applied[7]—meaning a slight loosening of tolerances could even jeopardize fatigue life. These studies quantify the sensitivity: **pitch (indexing) errors were often found to excite worse TE and vibrations than comparable profile errors**, for example[1]. Broadly, the conclusion is that **manufacturing deviations act as potent excitations**, and robust NVH predictions require treating key tolerances as random variables, not fixed values[1].

Another insight from statistical analysis is the interaction between different errors. Monte Carlo simulations have revealed **non-linear coupling** between error sources—e.g., a certain small pitch error combined with a particular profile deviation might amplify TE more together than each would alone. In one recent study, including both measured pitch errors *and* measured flank form error doubled the peak-to-peak TE, whereas each alone had a smaller effect[1]. This suggests a complex interaction that deterministic analysis might miss. Modern **Loaded Tooth Contact Analysis (LTCA)** tools can incorporate measured topography of teeth: a 2025 study by Im et al. showed that by importing actual measured tooth profile errors into the gear contact model, the static TE prediction matched bench tests to sub-micron accuracy[1]. This is an encouraging development—it validates that **including real manufacturing data (like profile error maps) greatly improves NVH prediction fidelity**[1]. However, it also highlights how important it is to gather such data and perform **numerical experimentation (DOE or Monte Carlo)** on it to understand variability effects.

Finally, robust design methodologies have been proposed to handle manufacturing scatter. Instead of optimizing a gear purely for best-case performance, **robust optimization** involves minimizing the sensitivity to variations. For example, tolerancing strategies can allocate looser tolerances to less sensitive parameters and tighter ones to critical ones, balancing cost and NVH. Six Sigma tools like **process capability indices (Cp, Cpk)** come into play here: a process with Cp/Cpk > 1.33 or 1.67 might be required for critical tolerances to ensure the majority of parts meet the NVH targets. If the process can’t hold that capability, the design must be adjusted (either modify geometry to be less sensitive, or change spec). In practice, **gear manufacturers combine tolerance design with inline metrology and statistical process control** to achieve consistent quiet gears[2]. The use of 100% end-of-line NVH testing on gears (especially for EVs) is increasingly common to catch any outliers[2]. All of these efforts tie into a simple principle: **a robust NVH design must incorporate manufacturing variations up front**, rather than treat them as an afterthought[1].

4. Gear Housing Variations and Radiated Noise

While gear imperfections drive the source excitation, the gearbox **housing** determines how that excitation turns into audible noise. The housing, usually a cast aluminum or magnesium enclosure, can have its own manufacturing variations—wall thickness deviations, rib positioning differences, material property scatter, etc. These affect the housing’s dynamic stiffness and modal frequencies, thus influencing the radiated noise.

Housing Wall Modes: It is well established that the dominant mechanism for gear radiation is through the housing wall vibrations[8]. The gear mesh forces transmit via shafts and bearings into the casing, causing it to flex and **act like a speaker**. In most cases, **flexural (bending) vibrations of the housing walls are the primary noise radiators**[8]. Thin, flat sections of the gearbox wall can behave like vibrating plates, especially at their resonance frequencies, pumping sound into the surroundings. Consequently, **increasing the stiffness and mass of the housing tends to reduce noise**, by pushing resonances to higher frequencies (where excitation is weaker) and by lowering vibration amplitudes[9]. For example, a heavier or thicker casing generally vibrates less for a given excitation, and added mass lowers overall radiation efficiency at low frequencies. Empirically, simply using a **more robust housing** (thicker walls, reinforcements) often yields a quieter gearbox—a known trade-off between NVH and weight.

However, housing dynamics are complex. A notable finding by NASA researchers is that making a wall thicker doesn't uniformly help at all frequencies. They observed that the **acoustic radiation efficiency** of a mode can increase at higher frequency[9]. In one case, **thickening a transmission housing shifted a wall mode to a higher frequency where its radiation efficiency was greater**, resulting in potentially *more* noise if the vibration reduction was not sufficient[9]. By contrast, some higher-frequency modes have nearly constant radiation efficiency, so altering thickness might simply reduce vibration and thus noise[9]. The takeaway is that one must consider *both* vibration amplitude and radiation efficiency. Generally, adding ribs or thickness lowers vibration, and usually that outweighs any efficiency gain (so noise drops), but engineers need to verify this with vibro-acoustic analysis rather than assume thicker is always quieter.

Impact of Wall Thickness and Ribbing Variability: Manufacturing tolerances in casting the housing can lead to slight wall thickness deviations or pattern differences in ribs (stiffening ribs inside the housing). Studies have shown even **minor changes (on the order of millimeters) in wall thickness or rib count can measurably alter the housing's vibrational behavior**[10]. In a lightweight EV gearbox, Albers et al. (2023) numerically evaluated several housing variants: adding ribs in certain locations, removing material in others[10]. They found that adding ribs generally **increased local stiffness and reduced vibrations**, whereas thinning walls or removing material to save weight invariably **increased vibration levels**[10]. Even the *arrangement* of ribs was critical—two designs with the same number of ribs could perform differently if the rib layout changed, due to different mode shapes being excited[10]. In short, **the housing's rib topology and wall thickness distribution are key NVH tuning parameters**, and small manufacturing-driven variations in these can move the needle on noise. One study noted that just reducing a rib's height by a few percent in one area made a particular wall mode more compliant, raising its vibration amplitude and noise[11]. On the other hand, increasing a rib's thickness at a strategic spot could split a loud resonance into two higher-frequency, lower-amplitude resonances, reducing overall noise.

From a practical perspective, **casting process variations** (like slightly uneven wall sections or core shift leading to one side being thinner) may lead to unit-to-unit variability in NVH. Quality control of castings to ensure minimum wall thickness and correct rib placement is therefore important for NVH consistency. It has been observed that lightweight designs can suffer "inferior NVH behaviour" if manufacturing variances push the housing out of its intended spec[10]. This motivates simulation of not just an "average" housing, but also worst-case or statistical variations—akin to gears. Some manufacturers now apply **modal testing on housings** in production audits to ensure the main natural frequencies haven't shifted undesirably due to a casting issue.

Radiated Noise Optimization: On the positive side, several publications have demonstrated that **optimizing housing geometry can yield substantial noise reductions** in practice. A recent example applied **topology optimization** to an EV gearbox housing: starting with a baseline design, material was strategically added or removed (within packaging constraints) to minimize radiated sound power[6]. The optimized housing introduced rib reinforcements in areas of high strain energy and increased some wall thicknesses. Tests on the prototype showed a **noise reduction of about 2.4 dB(A)** in the target frequency range[6]—a meaningful improvement[6]. Similarly, Kim et al. (2024)

report successfully shifting and reducing certain casing mode responses through shape optimization, confirmed by both simulation and physical tests within 0.2 dB[6]. These studies underscore that **modifying housing wall shapes and rib layouts (via FEA-based optimization) can directly lower radiated noise by a few decibels**[6]. Notably, such optimization has already been applied in an agricultural EV gearbox and is equally applicable to automotive transmissions. The key is a coupled **structural-acoustic analysis**: first simulate how vibrations change with design tweaks, then predict resulting sound via boundary element or similar acoustic models[6].

In all cases, a stiffer/heavier housing tends to push resonances out of the most sensitive range and reduce amplitudes, so the general guideline holds: **more robust housings yield lower noise** (albeit at odds with weight reduction goals)[10]. Automotive engineers therefore often face a multi-objective problem—meet NVH targets while minimizing weight. The solution might involve strategically placed ribs or contour changes rather than blanket thickening. For instance, one approach is adding **localized ribs** near high-strain regions (like around bearing seats or broad wall panels) to break up large vibrating areas. This can increase the damping and split resonant modes. Conversely, overly symmetric rib patterns can cause modes to cluster at single frequencies; introducing slight asymmetry sometimes spreads out the modal density and reduces peak noise. Thus, robust housing design considers **manufacturing variability** (to ensure every produced housing meets a minimum stiffness) and includes **NVH optimization features** that are tolerance-insensitive.

5. Integrated Gear-Bearing-Housing Modeling

To truly predict gearbox NVH, one must model the entire chain: gear excitation → transfer through bearings → housing vibration → radiated sound. **Integrated CAE models** that link gear microgeometry to system-level noise are increasingly reported. In such a model, the computed transmission error or mesh force (possibly from LTCA or a multi-body dynamics simulation) is applied to a finite element model of the gearbox structure, and then an acoustic solver predicts radiated noise. For example, Roldán (2018) used MSC Adams to take a gear's TE excitation and compute housing vibrations, then used a boundary element model to get far-field noise[1]. Tanaka et al. and Guo et al. developed similar workflows by feeding gear and bearing forces into an **FEA of the housing and a BEM (Boundary Element Method) acoustic model**, achieving reasonable correlation with measured sound[6]. These integrated approaches have become the virtual test bench for NVH, allowing engineers to evaluate how a given microgeometry modification or a tolerance scenario might affect the final sound pressure at the driver's ear.

Such models also highlight the importance of **boundary conditions** and assembly aspects. For instance, including the compliance of **bearings and shafts** is crucial—a rigidly mounted gear might show less TE amplification than one that's allowed to misalign slightly in its bearings. Petrone et al. (2020s) noted that housing elasticity can feed back and alter gear meshing behavior slightly (e.g., additional misalignment under load), thus a fully coupled model might iterate between gear contact and structural deflection. The consensus in recent literature is that **a high-fidelity NVH prediction must encompass gear, bearing, and housing dynamics together**[6]. This ensures that, say, a certain housing mode at 1200 Hz that aligns with a gear mesh harmonic is accounted for. Indeed, one NVH simulation case study found a particular housing lid mode was amplifying noise at a gear order; once identified, a minor design change to that lid eliminated the issue[3].

Validation of these chains is key. Many researchers perform **vibration modal testing and sound measurements** on prototype gearboxes to validate that the model's predicted natural frequencies, vibration amplitudes, and sound levels match the real world[6]. As mentioned, Im et al. showed excellent match in TE by including measured flank data[1]. Kim et al. achieved <0.2 dB error between simulation and test for housing noise[6]. Such validation builds confidence that the models can be used in design iteration to foresee NVH problems. Going forward, integrating **measured manufacturing profiles into these models** ("digital twins" of the as-built gears) is a promising approach to predict ghost orders and unit-to-unit variation. The goal would be a simulation that,

given the measured deviations of a gear set, can predict if that specific pair will be noisy—thereby enabling a feedback loop to manufacturing.

6. Robust NVH Design and Quality Assurance

The ultimate aim is **robust NVH performance** despite manufacturing scatter. This entails both *design-side* and *production-side* measures:

- **Tolerance Allocation & Stack-Up:** During design, engineers perform tolerance analysis specifically for NVH-critical parameters. For instance, they might allocate a tighter pitch error tolerance if analysis shows indexing error contributes strongly to TE and noise[1]. If certain errors (e.g., profile error) are less sensitive thanks to profile modifications, their tolerance could be relaxed slightly in favor of manufacturability[4]. Modern gear design software even allows “NVH quality” checks; e.g., Kisssoft can simulate how a gear at the tolerance limits would affect TE and contact pressure[12]. By setting NVH-driven tolerance limits, one ensures that any gear meeting print tolerances is also likely to meet noise targets (though as we saw, ghost noise can slip through standard tolerancing, thus sometimes **new metrics like flank waviness** must be specified).
- **Process Capability and Process Shift:** It’s not enough to set tolerances; one must ensure the manufacturing process can consistently achieve them. **Process capability indices (Cp, Cpk)** are used to quantify this. A high Cpk ($>>1$) means the process variation is well within spec limits, yielding a low reject rate and uniform output. For NVH, consistent processes mean less spread in TE and noise across production. However, processes can drift (mean shifts) or have tool wear effects. For example, a grinding machine might gradually introduce more lead error as the dresser wears. Robust design anticipates this by perhaps targeting a Cpk of 1.33 at half the allowed tolerance—providing margin for drift. Another strategy is **process corrections**: on-line measurements (like barkhausen or optical scans) can detect trends and allow proactive adjustment (e.g., tweak machine offsets) before parts go out of spec. In our large-scale production, it’s observed that **the combined effect of small gear and housing deviations leads to a distribution of NVH outcomes**; to keep that distribution tight (i.e., minimal variance in noise), processes must be tightly controlled and centered (minimum mean shifts)[2]. This often requires investment in high-precision machines, in-process gauging, and rigorous maintenance of machine calibration.
- **Inline and End-of-Line Inspection:** Leading transmission manufacturers now implement **100% NVH testing** of gearsets or even individual gears before assembly[2]. For example, a single-flank torsional vibration test can screen gears for ghost order excitations by measuring their acceleration spectrum at high speed[2]. If a gear produces spikes at certain orders, it can be marked as noisy and either scrapped or reworked. This approach effectively catches those outliers where, say, an undetectable flank anomaly would otherwise slip through. Additionally, traditional gear inspection (lead, profile, pitch measurements) is performed on every gear or statistically sampled to ensure conformance. **Inline metrology** (such as laser scanning or on-machine measurement) provides data to keep the manufacturing process in check and feeds back to design. The concept of “**measured performance drawing**” is emerging: instead of just yes/no tolerances, gear measurements can be fed into a model to predict if that gear will meet NVH requirements. Only gears with predicted high TE or ghost risk are filtered out, potentially allowing a slightly higher tolerance as long as the model predicts acceptability. This closes the loop between design prediction and quality control.

In summary, ensuring quiet gears in mass production demands a triad of **robust design, capable processes, and comprehensive quality assurance**. Gear and housing variations cannot be eliminated entirely, but by designing for insensitivity (where possible) and rigorously controlling and monitoring production, the NVH variability can be kept within a narrow band. A well-designed process might yield, say, 95% of gearboxes within a 3 dB noise range—whereas a sloppy one could

have some units 10+ dB louder than others. The latter is unacceptable for OEMs, hence the push for Six Sigma quality on NVH-critical features. As one recent industry article put it, *“the smallest deviations and waviness on the tooth flanks can lead to disturbing noise behavior”*—thus, **manufacturing consistency is as important as the nominal design in achieving quiet transmissions**[3].

7. Open Research Questions

Despite progress, several NVH challenges related to manufacturing variability remain open for research:

- **Predictive “Ghost Noise” Modeling:** While we can simulate ghost orders by inputting measured errors, doing so *predictively* (without measurements) is tricky. A full multi-physics model that captures gear manufacturing process signatures (e.g., grinder chatter patterns) and translates them into noise predictions is not yet standard. Researchers are working on linking machine tool errors to gear spectral error content. Moreover, replicating ghost order effects requires high frequency resolution and accounting for tooth-to-tooth variability—pushing the limits of current modeling. Improved techniques (or higher computational power) to include, for example, stochastic surface error representations in dynamic simulations would help here. **Boundary conditions** also matter: real gear pairs have varying support stiffness and backlash which influence ghost tones; modelling the range of these in operation (cold vs. hot, different mounting) is an ongoing area.
- **Direct Integration of Measured Topography:** Although one can now map measured 3D tooth surface data into simulations (as shown in research[1]), it’s not yet a routine part of design due to time and data size constraints. Future tools might integrate CMM measurements of gears directly into FE or MBD models in an automated way. This would allow **digital twins** of actual production units, enabling correlation of specific surface features with noise. One vision is that every gear gets a “fingerprint” and its expected noise can be forecast by simulating the measured geometry—then pairing of gears or targeted lapping could be done to mitigate any issues. Advancements in scanning speed and data handling, as well as model reduction (to condense a surface map into key error harmonics), will facilitate this.
- **AI and Explainable Diagnostics:** With the plethora of inspection data (profile plots, FFTs of TE, etc.), there is interest in applying machine learning to identify patterns that correlate with noisy gears. For example, an ML model could be trained on many gear measurements and their noise test results to predict NVH outcomes from measurements alone. Some initial work in this direction exists, but a challenge is making these models **explainable**—i.e., providing insight like “high amplitude of 5th-order waviness in profile is causing a ghost order”. Bridging AI with physical causation (XAI for metrology) would greatly help quality engineers introduce controlled amounts of “behavioral” modifications. Interestingly, as noted in a Marposs report, sometimes a **perfectly smooth gear can be noisier** than one with slight imperfections, because a touch of random “disorder” can damp certain resonances[2]. Understanding such counter-intuitive effects and guiding the manufacturing process (perhaps to intentionally introduce benign micro-variations) is a frontier. AI might detect when a gear’s spectrum is “too perfect” and likely to ring at a single frequency, vs. one with a mild broadband roughness that spreads energy.
- **NVH of New Manufacturing Methods:** As production evolves (e.g., additive manufacturing for gears, new heat treatments, composite housings), the nature of manufacturing variability changes. For instance, 3D-printed gears may have different error signature (layer-induced waviness). How these affect NVH and how to control them will need study. Similarly, lightweight composite or plastic housings will have different variability (material property scatter, joint tolerances) and acoustic radiation characteristics, raising new questions for robust NVH design.
- **Extending Robust Design to System Level:** We often tackle gear and housing separately in analysis, but ultimately the entire powertrain including e-motor, differential, mounts, etc., has

manufacturing variances. A holistic robust NVH model that includes motor shaft balance, gear errors, bearing preload variation, and housing modes together would be extremely valuable to predict the *overall* vehicle NVH variability. This is a complex, multi-disciplinary problem that likely requires new efficient simulation and uncertainty propagation techniques.

Case Study: Stochastic NVH Assessment from a 40k-sample Gear Tolerance Dataset

Dataset and objective

We analyze “**Gear Statistical tolerance analysis results (1).xlsx**” (N = 39,984 rows, 21 columns) to ground the article’s concepts in data. Each sample represents a combination of tolerance terms (pitch, runout, form on pinion/wheel), a **misalignment** term, and outcomes: **KTE value** (kinematic transmission-error proxy) and **Assembled conformity** (0–1).

Our goals are to (i) examine distributions and basic relationships, (ii) quantify linear and nonlinear effects of manufacturing variability on KTE, and (iii) discuss how the same dataset supports Monte-Carlo/bootstrapped NVH assessments and process-shift “what-if” studies.

Key descriptives. KTE: mean **22.501**, SD **4.330**, min **15.001**, max **30.001** (Figure S1). Assembled conformity: mean **0.412**, SD **0.387**, range **0–1**; its wide spread is consistent with mixed manufacturing capability across scenarios (Figure S2).

Empirical findings from the dataset

(1) Linear relationships are negligible

Pearson correlations between KTE and all tolerance/shift terms are essentially **zero** (top five $|r| \approx 0.001$; see Figure S3 and the correlation table). In other words, **no single variable** shows a meaningful *linear* relationship with KTE in isolation. This supports the view that TE/NVH is shaped by **weak, nonlinear, and interacting** influences rather than by any one tolerance acting alone.

(2) Nonlinear modeling highlights process shifts

A Random Forest regression using all tolerance and process-shift features yields $R^2 = 0.093$ and $MAE = 3.611$ (KTE units), indicating modest predictive power from these variables alone. Nevertheless, the model **consistently ranks process-shift terms highest** (Figure S4):

1. Misalignment process shift — importance 0.094
2. Crown wheel pitch process shift — 0.087
3. Crown wheel runout process shift — 0.080
4. Crown wheel form defect process shift — 0.078
5. Spur gear form defect process shift — 0.076

This aligns with engineering intuition: **assembly/alignment and mean-shift effects** perturb load sharing and contact conditions, thereby influencing TE even when simple linear metrics underreport the effect.

3) Monotone but small quartile trends

Binning the top RF drivers into quartiles (Q1→Q4) shows **small, monotone increases** in KTE with larger shifts (Figure S5):

- Misalignment process shift: **22.493** → **22.510** ($\Delta \approx +0.017$)
- Crown wheel pitch process shift: **22.496** → **22.505** ($\Delta \approx +0.009$)
- Crown wheel runout process shift: **22.496** → **22.511** ($\Delta \approx +0.015$)

Directionally consistent, these effects are **subtle** at the dataset’s scale, reinforcing the need for multivariate (interaction-aware) treatment rather than single-tolerance thinking.

Using the dataset as a stochastic demonstrator

Monte Carlo and bootstrapping for yield–NVH trade-offs

The dataset can be resampled (bootstrap/Monte Carlo) to estimate the **distribution of Assembled conformity** (yield) alongside the **distribution of KTE**. Plotting these (cf. Figures S1–S2) enables exploration of the **capability vs. NVH** trade-off: tighter composite capability targets typically push KTE lower but risk **lower yield**; looser capability relaxes production at the cost of **higher and**

more variable TE. Quantifying this curve directly from the data provides evidence-based targets for manufacturing and design.

Global sensitivity analysis (GSA)

Beyond RF importances, variance-based methods (e.g., **Sobol**, **PAWN**) can apportion KTE variance to inputs and their interactions. Literature often ranks **tooth indexing/pitch error** and **runout** as leading TE drivers, with **misalignment** significant through contact pattern effects [1,12]. Applying GSA here would complement Figures S3–S5, turning qualitative importance into **variance shares** and clarifying interaction terms.

Process-mean shifts and centering

Because the dataset includes **process shift** terms, it naturally supports “**what-if**” evaluations of centering vs. drift (e.g., shift ≈ 0 vs. 0.8). Centered processes typically raise **conformity** ($C_p \approx C_{pk}$), while drift towards limits lowers **Cpk** and increases out-of-spec risk—especially under tight tolerance stacks [2]. Combining shift scenarios with Monte Carlo draws gives practical yield forecasts to guide **feedback control** and **process adjustments**.

Extending to housing variability

While these data focus on gear errors and misalignment, the same workflow can incorporate **housing variability** (e.g., wall-thickness tolerance as a stiffness proxy). A simple extension introduces a “housing amplification factor” as another random input; even with perfect gears, a more flexible housing may radiate more sound. Industry experience and prior studies emphasize that **both gear quality and housing dynamics** must be managed jointly for robust NVH in production [10].

Takeaways and implications

- Single-variable linear effects are not the story. With near-zero Pearson r , KTE depends on weak, nonlinear, and interacting contributors.
- Process shifts matter. Despite low R^2 , nonlinear modeling and quartile trends consistently elevate misalignment and crown-wheel pitch/runout shifts as the most actionable levers.
- Design for capability. Use the dataset for Monte Carlo/GSA to set evidence-based NVH targets that respect manufacturing capability (yield) and process centering.
- System view. Extend the analysis to include housing and other boundary-condition variability for end-to-end NVH robustness.

8. Conclusions

Manufacturing variability plays a pivotal role in geartrain NVH—it **forms the critical bridge (or gap) between theoretical simulation and production reality**. Gear tooth errors like pitch, runout, profile and waviness, even when kept within drawing tolerances, **systematically increase transmission error and can generate ghost order noises** that are particularly conspicuous in the near-silent backdrop of EV powertrains[3][2]. Likewise, variations in the gearbox housing’s stiffness due to wall thickness or ribbing changes can reshape vibrational modes and significantly influence radiated noise—generally, **more rigid (heavier) housings tend to lower noise**, whereas lightweight designs must be optimized carefully to avoid loud resonance peaks[8][10]. Bridging these insights, modern robust design practices treat manufacturing imperfections not as afterthoughts but as design inputs. By incorporating statistical tolerance analysis, Monte Carlo simulations, and worst-case scenarios into the NVH design phase, engineers can develop gearboxes that are not only quiet in prototype tests but remain quiet across thousands of production units. On the factory floor, ensuring high process capability, employing thorough gear inspections (including advanced NVH tests), and maintaining tight control of process drifts are all essential to achieve the NVH consistency targets.

In closing, the quest for “uniformly quiet” transmissions at mass-production scale is an interdisciplinary challenge: it demands gear design optimization, materials and process engineering, precise metrology, and even data science for pattern recognition. The benefits, however, are clear—meeting stringent NVH requirements reliably, reducing scrap and rework costs, and delivering a refined customer experience. As one comprehensive review summarized, **manufacturing tolerances and uncertainties are indeed crucial factors for gear NVH performance, and explicitly accounting**

for them is key to robust gear design optimization[1]. The continued convergence of simulation and production (through digital twin models, real-time quality data feedback, and intelligent process control) will further narrow the “simulation-reality” gap. Future research and development, as outlined, will focus on predictive models for ghost noise, integration of measured data into simulations, and AI-driven diagnostics—all aiming to ensure that the NVH of a transmission can be dialed in, maintained, and guaranteed *before* the first part rolls off the assembly line. Such advancements will form the next step change in delivering quiet, efficient, and reliable powertrains for the modern age.

Key Takeaways:

- Gear manufacturing errors (pitch, runout, profile, waviness) directly raise transmission error and **cause tonal excitations (mesh harmonics and ghost orders)**; in EV gearboxes, these small variations can produce clearly audible noise and must be tightly controlled[3][2].
- **Housing stiffness variability** (wall thickness and ribbing differences) alters the vibration modes—a stiffer or more massive housing generally emits less noise by reducing wall flexing[8]. Even minor design or tolerance changes in ribs and walls can change NVH behavior, so robust designs often add ribs or thickness strategically to ensure consistency[10].
- Achieving robust NVH performance requires **incorporating manufacturing variability into the design process** and ensuring high process capability. By designing with tolerances in mind, using Monte Carlo analyses, and implementing thorough quality control (inline metrology, end-of-line NVH testing), manufacturers can produce quiet gearboxes consistently[1][2].

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