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Multiphysics Modeling of Gearbox NVH in Electric Drivetrains: Methods, Tools, and Trends

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Abstract

In modern electric vehicles (EVs), where the absence of a combustion engine reveals new acoustic challenges, gear and gearbox noise—especially tonal "whine"—has emerged as a prominent NVH (Noise, Vibration, and Harshness) concern. This review investigates the state-of-the-art multiphysics simulation workflows capable of predicting NVH from root excitation through structural vibration and up to radiated airborne noise. Emphasis is placed on software ecosystems developed between 2015 and 2025, including Romax, AVL EXCITE, Siemens Simcenter, SMT MASTA, MSC Adams/Nastran/Actran, KISSsoft + RecurDyn, and COMSOL Multiphysics. The review explores simulation layers ranging from analytic torsional models to coupled flexible multibody dynamics (MBD), finite-element structural response, and acoustic FEM/BEM methods. Recent trends such as per-tooth microgeometry definition, flank waviness modelling, use of measured topography (e.g., CMM data), and digital twin concepts are discussed in depth. Furthermore, the review highlights validation challenges—especially the limited system-level correlation between predicted and measured noise—and identifies research gaps regarding EV-specific excitations, manufacturing variation modeling, and NVH-oriented design optimization. This work aims to give engineers and researchers a structured overview of integrated CAE methods to "front-load" gearbox NVH prediction in electrified drivetrains, thereby improving design cycles and acoustic performance.

Keywords: gear NVH; gearbox simulation; electric vehicle noise; multiphysics modeling; gear whine; microgeometry; acoustic FEM/BEM; gear mesh excitation

1. Introduction

Noise, vibration, and harshness (NVH) in geared transmissions has become a critical concern, especially in modern electric vehicles (EVs) where the absence of an engine masks nothing – gear whine can suddenly emerge as a prominent source of cabin noise [1]. In EV drivetrains, high-speed gears under constant motor torque can produce tonal "whine" that is readily apparent without the cover of combustion noise. Ensuring quiet operation is not only a comfort and quality issue but also increasingly a regulatory focus (for example, as overall vehicle noise levels drop, tonal components stand out more). Traditionally, gear NVH was addressed by improving design for smooth power flow, but the **shift to electrification has raised the performance bar**. EV NVH problems demand **multi-disciplinary solutions**: the interactions of mechanical gearing, electric motor excitations, and acoustic response must all be considered [1]. Consequently, there is a marked move from isolated analysis (e.g. examining only a gear pair or only the motor) toward integrated *multiphysics* simulation of the entire system. Today's CAE toolchains increasingly aim to model the full noise generation chain – from the root excitation (gear mesh or electromagnetic forces) all the way to radiated sound – within unified workflows [2]. The overarching motivation is to "front-load" NVH considerations: to predict and prevent noise issues early in the design, before prototypes or end-of-line testing.

This paper provides a **literature review of multiphysics gear and gearbox NVH simulation pipelines**, with a focus on the 2015–2025 period. We examine how modern software ecosystems and methods tackle the NVH problem spanning **excitation → gear dynamics → housing vibration →**

radiated noise. The review highlights the capabilities of major commercial tools (Romax, AVL EXCITE, Siemens Simcenter, SMT MASTA, KISSsoft/RecurDyn, MSC Adams/Nastran/Actran, COMSOL, etc.) and recent trends such as modeling micro-geometry and manufacturing variations, and the emergence of digital twin approaches. We also discuss the **validation status and gaps** – i.e. how well these simulations have been correlated with physical measurements – and identify open research directions. Our aim is to give both researchers and practicing engineers a consolidated view of the state-of-the-art in simulating gear whine and related phenomena in a *multiphysics* context, bridging traditionally separate domains (mechanical, structural, acoustic, and even electromagnetic). The remainder of the article is structured as follows: Section 2 provides background on gear/gearbox NVH fundamentals and classical analysis approaches. Section 3 outlines the methodology of the literature search. Section 4 reviews the different levels of modeling (from lumped parameters to fully coupled FE/BEM). Section 5 compares several **software workflows** from excitation to noise. Section 6 discusses **recent trends** (micro-geometry, waviness, digital twins, EV-specific factors). Section 7 summarizes the **validation status** of these methods. Sections 8 and 9 provide a broader discussion, research gaps, and future directions, and Section 10 concludes the review.

2. Background on Gear and Gearbox NVH

Gear Mesh Excitation and Transmission Error: The dominant source of tonal noise in gear drives is the variation in tooth meshing forces, typically characterized by the gear's **transmission error (TE)**. TE is the slight deviation between the actual angular position of the driven gear and the position it would ideally have in a perfect, rigid mesh [3]. Even a perfectly manufactured involute gear will exhibit some TE under load due to tooth deflections and finite stiffness. Any imperfection in tooth geometry – such as profile errors, lead (alignment) errors, or eccentricity – introduces additional TE, which in turn creates a fluctuating mesh force at the tooth meshing frequency (and its harmonics). **Gear whine** is the radiated noise that results from these periodic mesh forces exciting the system. Designers have long applied **micro-geometry corrections** (e.g. slight **tip relief**, crowning, lead modifications) to gears in order to minimize load-dependent TE peaks [3]. An *ideal* gear pair under uniform load would have near-zero TE and thus be silent; in practice, micro-geometry tweaks can reduce TE but not eliminate it entirely. Additionally, manufacturing deviations like slight **waviness** or **run-out** on teeth can cause a varying TE even under no load – these kinematic errors lead to the so-called **"ghost tones"** (sideband whine at frequencies not equal to the main mesh harmonics) and are an increasingly recognized NVH issue in high-quality gears (addressed further in Section 6) [3]. Besides TE, another inherent excitation is the time-varying mesh stiffness as teeth come in and out of contact; this modulation can amplify certain resonance frequencies of the system [4]. Overall, a key NVH metric at the gear design stage is the **loaded transmission error curve** (often measured in microns or arcseconds): it serves as a proxy for potential whine excitation. Reducing TE, especially at critical orders, tends to correlate with lower radiated noise – though it is not a guarantee of silence if other factors intervene.

Drivetrain Dynamics and Housing Vibrations: The gear pair is only one part of the NVH story – the way the rest of the drivetrain responds is equally important. The oscillatory mesh forces pass through the **shafts and bearings** to the gearbox housing, exciting structural modes. For example, a gear set with perfectly minimal TE could still be noisy if it sits in a very lightly damped housing that resonates at the mesh frequency. **Bearing stiffness and misalignment** play a role as well: any misalignment or compliance in bearings can cause uneven load sharing across teeth and additional dynamic forces. These aspects can introduce their own frequencies (e.g. a shaft bending mode or a bearing natural frequency) into the vibration spectrum. In essence, the gearbox behaves like a complex spring-mass system: gears, shafts, bearings, and casing all have flexibility, and their coupled dynamics determine how the initial excitation (TE-driven mesh force) is amplified or attenuated [1]. A rigid housing will transmit high-frequency forces efficiently (leading to more high-frequency noise), whereas a very compliant housing might filter those but could exhibit low-frequency modes that radiate as booming noise. **Housing vibration** is often measured via accelerometers in both

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simulations and tests; it serves as an intermediate indicator of NVH performance. A common metric is the acceleration or velocity at specific points on the housing (e.g. near a bearing location) and the associated frequency spectrum. If a particular gear design change reduces the acceleration at the mesh frequency, it's a good bet that radiated noise at that frequency will also drop. However, one must be cautious: sometimes a design change can *shift* a resonance rather than eliminate it, potentially trading one problematic frequency for another.

Radiated Noise and Acoustic Metrics: Ultimately, what matters for the end user is the **airborne noise** that reaches the ear. Gear whine typically manifests as tonal noise (pure-tone or narrow-band sounds) at the gear mesh frequency and its harmonics (e.g. if a gear mesh frequency is 500 Hz, whine might be heard at 500 Hz, 1000 Hz, 1500 Hz, etc.). In electric drivetrains, these tones can be quite prominent. Engineers quantify radiated noise via metrics like **sound pressure level (SPL)** in dB at a standard distance, or **sound power** in watts. In simulations, an acoustic finite-element or boundary-element analysis can predict the sound pressure at a "virtual microphone" point or the total sound power. A practical example is comparing the predicted **housing surface velocity** and resulting sound power for different designs – a design yielding lower overall sound power or SPL at key frequencies is preferred. NVH evaluations also increasingly consider **psychoacoustic metrics**: for instance, two gearboxes might have the same dB level, but one has a pure tone (high *tonality*) that is more annoying. Thus, simulations sometimes compute tone metrics or loudness to reflect perceived sound quality. However, the fundamental output of most gear NVH simulations is a spectrum of either vibration or acoustic pressure. For instance, Marano et al. (2022) present comparisons of predicted vs. measured sound spectra for an axle drive, using the **sound pressure level vs. frequency** as the key metric [5]. In summary, important NVH performance indicators include: peak amplitudes at specific orders (e.g. the first mesh harmonic), overall sound power, and possibly modulation or sideband content (for ghost tones). A gearbox that minimizes these across the operating range is considered "quiet." Traditionally, achieving this meant iterating empirically on micro-geometry and housing design; increasingly it is achieved via simulation-driven optimization.

Classical vs. Multiphysics Approaches: Early gear NVH analyses often relied on **simplified, uncoupled models**. For example, one classical approach is a lumped-parameter *torsional model* – the gear pair is represented by a spring (mesh stiffness) and masses (gear inertias), maybe with a damper, to estimate resonances and dynamic transmission error. Similarly, empirical formulas (dating back to the 1970s–1980s) exist to estimate radiated noise from measured vibration, essentially by applying a factor to account for average housing radiation efficiency. These methods are fast and useful for conceptual design, but they **lack detail and accuracy**. A lumped model cannot capture the bending of a gearbox wall or the 3D acoustic radiation pattern, for instance. As a result, such methods might predict overall trends but **cannot reliably predict absolute noise levels or high-frequency content** [4]. Over the past decade, there has been a clear evolution toward *multiphysics* modeling: linking detailed gear contact analysis (to get accurate excitation forces) with flexible body dynamics (to simulate shafts/housing) and acoustic solvers (to predict noise). This progression mirrors the increasing computational power and the NVH demands of quieter electrified powertrains. The subsequent sections delve into these advanced methods – but it is important to keep in mind the foundational concepts described here. Gear whine starts at the tooth contact and ends as an acoustic wave; effective simulation needs to capture that entire path.

3. Methodology of the Literature Search

Our review methodology was a narrative literature survey combining academic research databases with industry sources. We queried scientific databases including **Web of Science**, **Scopus**, **IEEE Xplore**, and **Google Scholar** for keywords such as *"gear whine noise simulation"*, *"gearbox NVH"*, *"drivetrain acoustic analysis"*, *"electric vehicle gear NVH"*, *"digital twin gearbox"*, and related terms (in English). The time window was primarily **2015–2025**, reflecting the most recent decade of development in multiphysics NVH tools. Older, foundational works (pre-2015) are referenced sparingly for background context. In parallel, we surveyed **industry publications and white papers** from gear and CAE software vendors – for example, technical articles from Gear Technology and Gear Solutions magazines, as well as application notes by software companies (Hexagon/Romax, AVL, Siemens, SMT, etc.). These trade publications often contain state-of-practice insights not found in academic journals [3]. We also included a few **conference papers** (such as SAE technical papers and proceedings of ISMA, IFToMM, etc.) that presented relevant case studies or benchmarking of simulation methods.

In terms of inclusion criteria, we focused on sources that addressed **the simulation of gear or gearbox NVH with a multiphysics scope** – i.e., involving more than one physical domain (structure, acoustics, gear contact, or electromagnetics). Purely experimental papers on gear noise were considered only if they provided data for validation discussions. The literature search emphasized passenger vehicle and electric drive applications (since NVH is most critical there), but we also included some works on general gearbox noise (e.g., in transmissions or gear pumps) for broader context. After collecting an initial pool of sources, we filtered for uniqueness and quality: priority was given to **recent journal articles, high-impact conference papers, and substantive vendor technical documents**. Approximately 60–70 sources were reviewed in detail, from which we cite representative examples in this article. All source material was in English. Given the interdisciplinary nature of the topic, we cross-checked that our coverage spans the gear design community, the vibro-acoustic engineering community, and the software engineering domain. The reference list reflects this diversity, including academic studies and industry case reports. We acknowledge that some proprietary developments (especially within commercial software) may not be fully documented in public literature; we have noted such gaps where appropriate and relied on the best available information from user conferences or release notes in those cases.

4. Multiphysics NVH Simulation: Levels and Modeling Approaches

To predict gear whine from first principles, one must typically chain together several modeling levels. These range from analytical approximations to full numerical simulations. Here we outline these **simulation levels**, noting their roles and coupling.

Analytical and Reduced-Order Models: At the simplest end, engineers use lumped-parameter or analytical models to get quick NVH estimates. A classic example is a **torsional vibration model** of a gear pair, where the gear mesh is represented as a nonlinear spring (with stiffness that might vary with rotation) and the gears and shafts are reduced to inertia and spring elements. Such models can estimate resonant frequencies (e.g., gear pair bouncing or torsional mode) and sometimes even approximate the amplitude of vibration if a transmission error excitation is applied. Another analytical approach is to use **formula-based calculations** for radiated noise. For instance, one semi-empirical formula might compute overall sound power from the average vibratory velocity of a gearbox housing of given mass and damping. These methods are very fast and useful in early design screening. However, they **neglect many 3D effects** – e.g., mode shapes of the housing, directional acoustic radiation, etc. As noted in one study, simplified models often only predict an overall noise level and cannot capture the influence of housing geometry [4]. In practice, while an analytical model might tell a designer that "improving mesh alignment by X will reduce overall vibration," it will not reliably predict *by how many decibels* the noise will drop, nor will it identify new peaks introduced by complex modes. Therefore, analytical models are typically used in conjunction with more detailed methods as the design matures.

Flexible Multibody Dynamics (MBD): Most advanced gear NVH simulations rely on **flexible multibody dynamic models** to represent the drivetrain. In a flexible MBD model, the gearbox components (gears, shafts, bearings, housing) are represented as bodies that can move and deform, and their interactions (gear meshes, bearing contacts) are defined via force elements or contact algorithms. A common approach is to include the major elastic components as **reduced flexible bodies** using modal reduction (e.g., a finite element representation of the housing or gear blank is reduced to a set of mode shapes via Craig-Bampton method, and then imported into the MBD model). The multibody solver then computes the dynamic response in the time or frequency domain under the mesh excitation. For example, Marano et al. (2022) modeled an EV axle using a flexible MBD approach: the spiral bevel gears, shafts, and housing were all represented (the housing via a condensed FE model), and gear contact was handled with a penalty contact algorithm [5]. This allowed them to predict how vibrations at the gears transmit to the housing and to evaluate changes like varying the pinion position. Flexible MBD strikes a balance – it can efficiently simulate the system-level dynamics with reasonable computation time, especially in frequency-domain (e.g., modal superposition or harmonic response) approaches. Most commercial tools (Romax, EXCITE, Simcenter 3D, etc.) have an MBD core where users assemble a virtual gearbox, input gear mesh excitations (as a stiffness or transmission error), and obtain system vibrations. The output of such models often includes shaft or housing acceleration spectra, which are then candidates for acoustic analysis. One benefit of MBD models is that they readily capture **system resonances and coupling** – for instance, a gear pair might excite a bending mode of the shaft, or a housing mode might amplify bearing forces. These effects are included inherently. However, a limitation is that accurate results depend on feeding the correct excitation (gear mesh force or TE) into the model and having good estimates of damping and stiffness for components and joints. Many MBD approaches use measured or FE-calculated stiffness for bearings and meshes to improve fidelity [6]. In summary, flexible multibody simulation is a cornerstone of gear NVH prediction, forming the “middle” of the excitation-to-noise chain by translating gear forces into structural vibrations.

Structural Finite Element Analysis (FEA): While MBD handles system dynamics, detailed **finite element modeling** is often used to analyze specific components like the gear blanks or the gearbox housing. FE structural analysis can provide **modal characteristics** (natural frequencies and mode shapes) of the housing, which is critical for NVH. For example, an FE modal analysis might reveal that a gearbox housing has a mode at 1,000 Hz that involves the side walls vibrating outward – if the gear mesh frequency coincides with that, a loud whine might occur. FE models are also used to calculate **mesh stiffness** accurately (through tooth contact analysis) and even the dynamic load distribution across the tooth surface (via transient contact analysis). In the context of multiphysics NVH simulation, FE results are typically used in two ways: (1) *coupled into an MBD model* – e.g., a condensed housing model provides the flexibility in an MBD simulation – or (2) *stand-alone*, to assess a design’s modal alignment and perhaps perform **harmonic response** analysis (applying a unit force at the mesh location and seeing how the structure responds across frequencies). A structural FE model of the entire gearbox is possible, but that becomes quite large; more common is to include one or two flexible bodies in an MBD model. The trend is towards **hybrid approaches** that leverage FE where needed. For instance, Siemens Simcenter’s drivetrain workflow uses FE-calculated mesh stiffness maps or mode shapes in conjunction with faster system simulation [3]. Similarly, one can do a two-step approach: first run an FE contact analysis to get a precise transmission error curve, then feed that as an excitation into a multibody model. The structural FE step ensures that geometry details (ribs, thickness, etc.) are accounted for in the stiffness and mass distribution, which pure analytical models might miss. It’s worth noting that including detailed FE models increases computational cost, so engineers must choose the level of detail wisely.

Acoustic Simulation (FEM/BEM): To predict the radiated noise from a vibrating gearbox, acoustic simulations are employed, typically using either **boundary element method (BEM)** or **finite element method (FEM)** for acoustics. In an acoustic simulation, the vibratory response of the structure (usually the surface velocities of the gearbox housing) is taken as an input, and the sound pressure field in the surrounding air is computed. BEM is often favored for exterior acoustics since it automatically satisfies the radiation condition at infinity and requires discretizing only the surface of the radiator (the gearbox) rather than the volume of air. Many NVH workflows use a BEM solver (like LMS Virtual.Lab Acoustics, MSC Actran, or COMSOL’s acoustics module in BEM mode) to predict a **sound pressure spectrum at a field point or the overall sound power**. For instance, Mori et al. (2023) combined a multibody dynamic analysis in the time domain with a BEM acoustic analysis in frequency domain to predict the noise from a gearbox [4]. They found that increasing the rotational speed shifts the harmonic noise components to higher frequency and increasing the torque predominantly raises the amplitude of radiated sound (intuitively, more force = more noise) without changing the frequencies – insights that their simulation could provide. Acoustic FEM is an alternative when dealing with enclosed sound fields (like interior noise in a vehicle) or when BEM might be less efficient; it involves meshing the air volume and solving for pressure, often with absorbing boundary conditions to simulate anechoic space. In either case, acoustic simulation adds another layer of complexity – it requires accurate vibration data as input and proper handling of phenomena like acoustic resonances or directivity of sound. The **output** of an acoustic simulation is typically sound pressure levels at various frequencies (a spectrum), which can be directly compared to microphone measurements in tests. One challenge is that small errors in the structural vibration prediction can lead to noticeable differences in acoustic output (because acoustic radiation efficiency can vary sharply with frequency). Nonetheless, incorporating acoustic analysis is essential for a true end-to-end prediction of gear whine. In a fully coupled approach, one could even include the fluid-structure interaction (i.e., let the acoustic load feed back on the structure), but for gear whine (with relatively low acoustic back-reaction) this is usually unnecessary.

Fully Coupled Multiphysics Workflows: Bringing the above pieces together, the most advanced simulations create a **pipeline from excitation to sound**. In practice, this might be a sequential coupling rather than a single monolithic model. A typical *full-chain* simulation might work as follows: a gear contact model (analytical or FE-based) produces a **time-varying mesh force or transmission error** curve; this is fed into a flexible multibody model of the drivetrain, which calculates the **vibration response** of shafts and housing; the resulting surface velocities of the housing are then used by an acoustic solver to predict the **radiated noise spectrum** [3]. Some implementations iterate or co-simulate between steps (for example, updating the contact force if the housing deformation significantly affects gear alignment). Industrial software often streamlines these connections – for instance, Romax or AVL EXCITE can directly export a **nodal velocity field** to an acoustic solver, or even include a built-in acoustic post-processor. The Simcenter platform similarly enables running a structural and acoustic analysis in one environment. The end result is a prediction like "overall sound pressure level = 72 dB at 1 m, dominated by the 5th gear mesh harmonic" – a rich set of information that can guide design decisions. These fully coupled simulations are computationally intensive and require careful validation, but they are increasingly feasible with modern computing power. A key strength is the ability to perform *parametric studies*: for example, one can virtually test different micro-geometry modifications or different housing rib designs and see which yields the largest noise reduction [6]. One case study (referenced later in Section 6) demonstrated linking measured surface error data into such a simulation chain to predict ghost tone noise, illustrating the sophistication of current methods. In summary, the hierarchy of modeling approaches runs from simple analytic formulas to detailed coupled FE/BEM simulations. In the following section, we review how these are implemented in specific software **workflows**, each with their own history and emphasis.

5. Software Ecosystems and Workflows from Excitation to Radiated Noise

Modern CAE software packages offer various integrated workflows to simulate gear and gearbox NVH. Here we survey several major toolchains, highlighting their capabilities and typical use in going from gear excitations to radiated noise. Each of these "ecosystems" tends to have strengths in certain domains (e.g., gear contact vs. acoustics) and they often can be linked together to cover the full multiphysics span.

5.1. Hexagon Romax (RomaxDESIGNER, Enduro, Spectrum)

Romax Technology (now part of Hexagon) has developed a family of tools widely used for drivetrain analysis, with a strong focus on **system-level gear/bearing modeling and NVH**. Romax software allows engineers to build a complete geared **driveline model** (gears, shafts, bearings, housing, etc.) and analyze everything from durability to dynamics within one environment. For NVH, the flagship is **Romax Spectrum**, an add-on that performs frequency-domain NVH analysis on top of a RomaxDESIGNER model. According to Hexagon's literature, Romax Spectrum provides *full system powertrain NVH simulation, from gear and electric machine design through to radiated noise* [7]. In practice, a typical Romax NVH workflow will calculate the **gear mesh excitation** internally (either via built-in empirical mesh stiffness or a more detailed loaded tooth contact analysis in Romax Enduro) and then compute the forced response of the system (often via modal analysis of flexible components). Romax can include **flexible bodies** for shafts or housings (imported from FE), and it has close integration with bearing models and gear micro-geometry inputs. One notable capability of Romax is its partnership with electromagnetic simulation tools for **eDrives** – it can import electric motor vibrational forces (e.g. from Motor-CAD or JMAG) so that **motor torque ripple and magnetostriction forces** are included alongside gear mesh forces [8]. This is crucial for EV NVH where motor "whine" and gear "whine" occur together. In terms of acoustic output, Romax itself does not solve the acoustic field, but it can export excitations or structure vibration results to acoustic solvers. Some case studies demonstrate using Romax's predicted transmission error spectra as input to an acoustic BEM model, or vice versa, using Romax's predicted housing vibration and computing sound via Actran. In recent years, Romax has also embraced **manufacturing variation** modeling: for example, Romax Enduro can take per-tooth micro-geometry inputs (profile or lead deviations for each tooth) and predict the resulting system vibration [3]. A published case study by Hexagon and Tümosan (a tractor manufacturer) showed that importing **measured flank topography** into Romax Enduro and Spectrum enabled a better match of predicted vs. measured gear whine orders [3]. In summary, Romax provides a highly integrated workflow with a focus on *gear-centric* accuracy (detailed gear and bearing models) at the system level. Its strength lies in quickly evaluating NVH performance for different gear designs or assembly conditions in a single software. Many automotive OEMs and suppliers use Romax to identify problematic gear orders or gearcase resonances early in the design, then mitigate them by adjusting micro-geometry or structural ribs. The limitation is that for final acoustic quantification (dB levels, etc.), one might need to couple Romax results to a dedicated acoustic solver, as Romax's native capabilities are more about predicting vibration and order content. Nonetheless, Romax is often considered a **benchmark tool for gear whine** – if a potential gear design shows high TE in Romax and excites a housing mode, one can be fairly confident it would be noisy, and vice versa.

5.2. AVL EXCITE (EXCITE M for MBD + EXCITE Acoustics)

AVL's EXCITE is another widely used platform, originally developed for engine crankshaft and powertrain dynamics, that has extensive capabilities for **gearbox NVH**. AVL EXCITE™ **Powerunit/Transmission** (often just called EXCITE M for the multibody solver) allows building a flexible multibody model of the drivetrain, similar to Romax, with support for modal reduced flexible bodies and detailed **gear contact models**. One distinguishing feature is AVL's sophisticated gear contact algorithm (the **Advanced Cylindrical Gear Joint** in EXCITE) which can account for non-linear contact stiffness, backlash, and even partial tooth contact under deflection [9]. EXCITE is frequently used for **e-axle NVH** in the automotive industry; for example, it can simulate an entire e-powertrain including the electric motor, two-stage reduction gears, bearings, and housing flexibility. A notable strength of EXCITE is its built-in integration with an acoustic solver: **EXCITE Acoustics** can take the structural vibration results (e.g., surface velocities of the housing or forces on a rigid test bench) and perform a boundary element acoustic analysis to predict radiated sound. This means one can go from gear mesh forces to a dB spectrum in a (relatively) seamless process within AVL's environment. AVL has continuously enhanced EXCITE's ability to handle fine details. In the **2023 R1 release**, they introduced an explicit model for **gear flank surface waviness** – users can now superimpose a sinusoidal waviness pattern on a gear tooth surface and EXCITE's contact model will include its effect on transmission error and dynamic forces [10]. This is particularly important for capturing ghost tones from manufacturing errors. They also have features for micro-geometry (profile modifications, flank line deviations) and gear mesh misalignments. On the electric drive side, EXCITE can incorporate **electromagnetic excitations**: recent versions allow simulating the effect of

PWM inverter switching on motor torque output and vibrations [10]. Essentially, one can include the torque oscillation from a motor's control strategy as an input in the NVH model – thus evaluating, say, different PWM frequencies and their impact on gear noise. EXCITE's typical workflow for a gearbox NVH analysis would be: perform a static loaded contact analysis to get baseline TE and contact forces, run a transient or frequency response analysis of the multibody model (gears and shafts flexible, housing flexible) to get vibrations, then run EXCITE Acoustics to get noise at a microphone or sound power. If needed, those results can be visualized as an order spectrum or even played back as sound (through auralization tools). In terms of validation, AVL EXCITE has been extensively used in industry, and internal validations have shown good correlation for component-level results like bearing forces and housing vibration spectra. Open literature using EXCITE includes, for example, e-axle case studies where predicted acceleration levels on the housing were compared to measurements with reasonable agreement. However, full **radiated noise correlation** in open publications is limited (often due to proprietary data). Nonetheless, EXCITE is regarded as a **high-fidelity tool**, particularly valuable when the interaction between different subsystems (gears, bearings, motor) is non-trivial. One challenge of using EXCITE is the expertise required – setting up a full model with all the correct boundary conditions, damping, etc., is complex. But once set up, it provides a wealth of insight, from identifying a resonance (and suggesting a housing stiffener) to evaluating a gear profile tweak to avoid exciting that resonance. In summary, AVL EXCITE offers a comprehensive and continually evolving environment for drivetrain NVH, with recent innovations targeting exactly the trends of interest (like micro-scale waviness and EV motor integration).

5.3. Siemens Simcenter (3D, Amesim, Testlab, Acoustics)

Siemens **Simcenter** is a broad portfolio that spans 1D system simulation, 3D CAE, and test integration. For gear and gearbox NVH, the most relevant pieces are Simcenter **3D** (the 3D CAE platform, which succeeded LMS Virtual.Lab) and Simcenter **Amesim** (1D simulation), plus Simcenter **Testlab** for correlating with measurements. Simcenter 3D includes dedicated transmission modeling capabilities – for example, a **Transmission Builder** module to facilitate creating gear pairs, shafts, bearings, and housings within the CAD/CAE environment [3]. One can perform **Loaded Tooth Contact Analysis** in Simcenter 3D for gear pairs (including spiral bevel and hypoid gears, which are notoriously complex), producing mesh stiffness or transmission error results. These can feed into a **flexible multibody** simulation within Simcenter 3D's Motion module, where flexible bodies (from Nastran or Ansys meshes) represent shafts and housings. Furthermore, Simcenter has a strong acoustic simulation heritage (from LMS): it offers **acoustic FEM and BEM** solvers that can be directly coupled to structural results. A hallmark of Simcenter's approach is the emphasis on *integrated workflows*. In a recent webinar, Siemens demonstrated analyzing an EV drivetrain's NVH by combining **electromagnetic analysis of the motor, multibody gear simulation, and acoustic radiation** all in series [2]. Essentially, Simcenter aims to be a one-stop solution where you can go from "electric currents to radiated noise" within a unified software stack. For example, one could use Simcenter MAGNET or a similar tool to get motor forces, import those into Simcenter 3D along with gear mesh forces, run a dynamic simulation, and then directly compute sound pressure in Simcenter's acoustic solver. This integrated capability is often termed a **digital twin** of the e-driveline. The Simcenter workflow also supports **hybrid modeling**: using measured FRFs or modal data to correct/augment the simulation. For instance, their **Virtual Prototype Assembly (VPA)** tool can combine empirical mount stiffness or measured component responses with the FE model to improve accuracy [2]. This is in recognition that pure FE models sometimes lack certain real-world effects (like joint damping or manufacturing variability), so incorporating test data (when available) yields a more predictive model. In terms of features, Simcenter 3D can account for **gear flexibility** (by meshing the gear bodies), **bearing nonlinearities** (via stiffness maps or co-simulation with Samcef for detailed bearing contact), and **gear micro-geometry** (profile/lead modifications can be specified and their effect on TE evaluated). It also has specialized support for **bevel and hypoid gears**, which historically required bespoke codes – Simcenter inherited capabilities from the acquisition of Romax's competitor

LMS, and further developed them. Engineers using Simcenter have reported, for example, successful prediction of a problematic gear whine in an EV reducer and its mitigation by changing a housing rib, all done virtually. One published white paper by Siemens PLM documents a case where **bevel gear whine** was analyzed by comparing different micro-geometry designs and correlating predicted TE to test measurements [3]. Simcenter's advantage is the *tight integration with testing*: because Siemens also provides test hardware/software, the simulation results can be directly auralized or compared to test spectra in the same framework, facilitating validation. A potential learning curve, however, is that Simcenter 3D is an expansive CAE environment – setting up a full multiphysics model might involve multiple modules and significant expertise (CAD, FE meshing, solver setup for motion and acoustics, etc.). The payoff is a very comprehensive simulation. In summary, **Simcenter** provides an end-to-end solution for gearbox NVH, combining detailed gear contact analysis, flexible multibody dynamics, and acoustic radiation in one toolchain. Its recent applications have focused on **EV drivetrains**, where the ability to incorporate motor noise and high-frequency effects (and to iterate designs quickly in the virtual domain) is particularly valued by OEMs striving to refine sound quality. The inclusion of human-centric NVH aspects (psychoacoustics) is also a Siemens focus – e.g., ensuring the simulation can predict not just dB but whether a noise will be noticed or deemed annoying – although this often remains a post-processing step using tools like Simcenter Testlab Sound Quality.

5.4. SMT MASTA

Smart Manufacturing Technology's **MASTA** software is a specialized tool for gearbox and driveline engineering, known for covering the entire workflow from gear design to detailed analysis. MASTA has gained popularity for its user-friendly interface combined with deep gear modeling capabilities. On the NVH front, MASTA historically offered loaded tooth contact analysis and system dynamic analysis (via its built-in multibody module called **DRIVA**) to evaluate things like transmission error, torsional vibration, and gear rattle. In the last few years, SMT has added significant new features turning MASTA into a **one-stop multiphysics NVH tool**. As of **MASTA v14**, the software includes an **Integrated Acoustic Analysis** module that allows users to go from gear mesh excitations to predicted **microphone sound pressure** results entirely within MASTA [11]. This is a notable development – previously, MASTA users would have to export housing vibration data to an external acoustic solver. Now, MASTA performs a boundary element analysis under the hood (using a Fast Multipole BEM solver) to compute radiated noise. Dr. Tom Harvey of SMT summarized the capability as: *"with MASTA 14 you can perform the complete calculation from the excitation at the gears and electric motor right through to microphone sound pressures – all in one tool."* [11]. This quote underscores how MASTA encapsulates the full NVH pipeline (even including e-motor excitations, as noted).

A typical NVH analysis in MASTA would proceed as follows: the user defines the gear geometry and micro-geometry (MASTA has robust tools for flank modifications and even reads measured topography), the software performs a **Loaded Tooth Contact Analysis (LTCA)** to compute transmission error and mesh stiffness under the given load, then the **dynamic simulation** (either a transient time-step or a harmonic analysis via modal superposition) runs to find the system's vibrational response. MASTA's dynamic module considers shaft bending, bearing stiffness (including complex behavior like spline coupling if present), and housing modes (the housing can be included as a flexible FE-imported component). The result is, say, a vibration spectrum at the housing surface. Then the integrated acoustic solver can take those surface vibrations and compute far-field sound. MASTA's acoustic solver is designed for ease of use – for example, it can automatically place a standard **ISO 3745 microphone array** around the housing and compute sound power or sound pressure at those points [11]. It also uses a **boundary element** approach that does not require a separate acoustic mesh; it maps the structural mesh to acoustic elements automatically [11]. This heavy automation is aimed at making acoustics accessible to gear engineers who may not be acoustic experts. The software still supports the older approaches: one can output an **Equivalent Radiated**

Power (ERP) estimate (a quick single-number metric based on housing vibration) for rapid comparison, and one can still export detailed results to third-party acoustic codes if desired [11].

Another trend MASTA embraced is integration of **electric machine models**. MASTA has an **Inbuilt Electric Machine Analysis** feature that was one of the first of its kind – it allows users to include basic models of electric motor behavior in the same simulation environment [11]. While not as elaborate as a full FE electromagnetic solver, it can account for things like torque ripple or cogging torques from a motor design and apply them to the drivetrain model. This means the effect of an e-motor's excitations on gear NVH (and vice versa, e.g. how gear torsional oscillations feed back to motor) can be studied in MASTA. The inclusion of motor effects, combined with gear mesh, bearing, and housing dynamics, makes MASTA well-suited for **EV axle NVH analysis** similar to Romax and EXCITE. MASTA also has unique features for **gear rattle** and transient NVH (they have a time-domain simulation for phenomena like spline loosening and backlash impacts). For example, their Advanced Time Stepping Analysis for Modulation (ATSAM) allows analyzing how planetary gear carriers or other time-varying effects modulate the vibration signal [11]. This is useful for complex transmissions like multi-speed EV gearboxes or hybrid gear trains where multiple meshes interact.

In terms of validation, SMT has presented examples where MASTA's predicted transmission error and vibration levels were compared to lab measurements (often through their involvement in projects or customer case studies). The integrated acoustics is relatively new, so published validation of the absolute noise prediction is limited so far. However, by allowing an engineer to do *everything* in one tool, MASTA encourages iterative validation – for instance, one could calibrate the housing damping in the model until the simulated housing frequency response matches a tap-test or modal test, then be more confident in the acoustic result. From a user perspective, MASTA's advantage is efficiency: it automates many steps (mesh generation, coupling, etc.) that otherwise would require manual meshing or scripting between different software. The trade-off is some loss of fine control – e.g., the acoustic mesh automation might not capture a very fine geometrical detail as a dedicated acoustic engineer might. But for most gearbox NVH purposes, the convenience is a major benefit.

In summary, **MASTA** has evolved into a powerful multiphysics platform for gear NVH, covering from micro-scale gear tooth effects up to full acoustic radiation. Its emphasis on user-guided automation (with sensible defaults and built-in workflows) makes it attractive in industrial settings where time is limited. The trends of the last few years – bringing acoustics in-house, integrating motor models, enabling tooth-level deviation inputs – are all reflected in MASTA's feature set, aligning well with the needs of modern EV transmission NVH engineers.

5.5. KISSsoft + RecurDyn Workflow

KISSsoft is a well-known gear design and analysis software (now part of the Gleason group) that traditionally focuses on gear geometry, rating, and basic Loaded Tooth Contact Analysis. On its own, KISSsoft can compute transmission error, root stresses, and other gear performance metrics. However, it does not simulate full system dynamics. To address NVH, KISSsoft has in recent years provided interfaces to multibody dynamics software, notably **RecurDyn** (by FunctionBay). The combination of **KISSsoft + RecurDyn** leverages KISSsoft's detailed gear calculations and RecurDyn's time-domain dynamic simulation capability. The typical process is as follows: **KISSsoft** performs a gear mesh excitation analysis – essentially calculating the **time history of transmission error or mesh forces** for the gears under certain conditions – and then exports this as an excitation into **RecurDyn**, where a flexible multibody model of the gearbox runs to determine vibrations and radiated noise. In KISSsoft's own description, it *"offers the possibility to perform an NVH assessment of gearboxes. The calculation of the noise excitation within the drive train is based on the forced vibration (transmission error), which leads to transient bearing loads"*, and *"these results are then transferred to the multi-body simulation program RecurDyn and applied to the flexible housing structure"* [6]. In RecurDyn, one would build a model of the gearbox with bodies for gears (which could be rigid or include modal flexibility), shafts, bearings, and crucially a **flexible housing** modeled via an imported FE mesh (e.g., a modal reduced representation of the gearbox casing). The bearing loads or mesh forces from KISSsoft are applied to

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the appropriate locations (for instance, as dynamic force at the bearing nodes). RecurDyn then simulates the system's vibrational **response in steady-state**, and it can output things like the velocity of the housing walls.

One key output that KISSsoft/RecurDyn emphasize is the **Equivalent Radiated Power (ERP)** on the housing surface [6]. ERP is a metric indicating how much acoustic power a vibrating surface would radiate if it were in an infinite baffle, and it is derived from the surface vibration velocity. In the workflow, RecurDyn can calculate ERP distribution or total ERP as a post-processing step on the housing's vibrational results. This helps engineers identify "hot spots" on the housing that are contributing the most to noise – often correlating with areas of high vibrational amplitude (for instance, a particular wall panel might be lighting up at a resonance). The visualization mentioned in the KISSsoft literature shows that the analysis can be carried out visually, *"with the advantage that structural weak points of the enclosure due to increased radiation can be quickly identified"* [6]. In other words, one can see which parts of the housing radiate the most, and then consider design modifications like adding ribs or damping treatment to those areas.

The focus of the KISSsoft+RecurDyn approach is strongly on **gear microgeometry optimization for NVH**. KISSsoft, being a gear design tool, allows the user to modify gear macro and micro geometry (tooth profile relief, lead crowning, pitch errors, etc.) and immediately see the effect on static transmission error. Through the NVH interface, one can then propagate that change to the dynamic simulation and see the effect on vibrational response and noise metrics. This capability is valuable because it connects gear design parameters directly to NVH outcomes. For example, an engineer can evaluate not just the usual "static transmission error" criterion, but actually how a profile modification reduces dynamic bearing forces and radiated noise in the context of the whole system [6]. This moves beyond the traditional gear design focus on minimizing *static* TE – it allows evaluation of *dynamic* behavior and noise, which is ultimately what matters. The KISSsoft-RecurDyn workflow has been demonstrated on e-drive applications in webinars and demo projects (e.g., an EV reduction gear where measured tooth surface topography was imported into KISSsoft, then NVH simulated in RecurDyn, and results compared with test bench noise – indicating a good correlation of dominant orders).

One advantage of this modular approach (using two specialized tools) is that each tool excels in its domain: KISSsoft has high-fidelity gear contact algorithms (including standards-based stiffness calculations and even allowances for flank modifications and manufacturing errors), while RecurDyn is a robust nonlinear multibody solver with efficient handling of flexible bodies and large models. By linking them, users get a fairly sophisticated NVH prediction without needing a full-blown vibro-acoustic FE model. It's also worth noting that RecurDyn itself can do acoustics by exporting data to an acoustic solver (FunctionBay provides an Acoustic Module and also supports exporting data to Actran or other acoustic tools). So, if needed, one could extend the chain KISSsoft → RecurDyn → Actran to get actual sound pressure levels. But many industrial users find evaluating **relative NVH performance** (via metrics like ERP or velocity levels) is sufficient for comparing design variants, even if they don't compute an absolute dB.

In summary, the **KISSsoft + RecurDyn** workflow is an example of a semi-integrated toolchain where gear design software and multibody dynamics software work in tandem to achieve a result similar to the all-in-one tools. It highlights the importance of **bearing loads and housing flexibility** in the NVH transfer path: KISSsoft computes the *excitation* (transmission error leading to bearing force fluctuation), and RecurDyn computes the *transfer and response* (how the housing vibrates and radiates). The trend that this workflow underscores is that **gear optimization for NVH** is now becoming feasible in early design – KISSsoft explicitly notes that *"NVH analysis now offers the additional possibility of evaluating the gearing not only in terms of static transmission error, but also in terms of dynamic behavior"* [6]. This is a significant shift for gear designers, bringing NVH into the design loop rather than something checked later by a separate group. The downside of a split workflow is the extra step of data transfer and possibly the need to be proficient in two different software interfaces, but user-friendly links (like a dedicated export/import function) have minimized this friction. From an adoption perspective, this approach may appeal to companies that already use KISSsoft for gear design and want to extend into NVH without investing in a completely new platform – they can add RecurDyn (or another MBD tool) to their toolchain and achieve many of the benefits of the integrated tools.

5.6. MSC Adams + MSC Nastran + Actran (Integrated Workflow)

Before dedicated gear NVH software became prevalent, many engineers constructed custom workflows using general-purpose CAE tools. A representative example is combining **MSC Adams** (for multibody dynamics), **MSC Nastran** (for structural FEA), and **MSC Actran** (for acoustic simulation). Each of these is a powerful tool in its own right, and together they can simulate the full NVH chain, albeit with more manual effort. In such a workflow, **Adams** (or a similar multibody solver like Siemens Simpack) is used to model the drivetrain kinematics and dynamics. Adams has gear pair elements (including models like **Adams/Gear** with stiffness formulations for spur and helical gears) and allows flexible bodies via modal reduction (using, say, CMS in Nastran). An engineer might start by generating **gear mesh force time histories** in Adams – either by using built-in contact (with a simplified stiffness curve) or by importing a user-defined force vs. angle profile obtained from a gear contact analysis. The multibody simulation would capture how those forces excite the system (e.g., causing the gearbox housing, included as a flexible body, to vibrate). The result could be time signals or spectra of acceleration on the housing.

Next, **MSC Nastran** (or an equivalent FE solver like Abaqus or ANSYS) would be employed for a more detailed **structural analysis** if needed. In some cases, one might perform a separate Nastran **modal analysis** of the housing or even a direct **frequency response analysis** applying forces (from Adams) to a detailed FE model of the entire assembly. There are also co-simulation approaches where Adams and Nastran iterate (Adams passes loads, Nastran returns deflections) to account for flexible coupling in the time domain. However, a more common approach is sequential: Adams provides the loads or motions, Nastran computes the structural vibration with finer resolution. For instance, an Adams run might identify that at 2000 RPM a certain mesh harmonic coincides with a housing mode; then a Nastran harmonic analysis can be done at that frequency to predict stress or refine the mode shape understanding.

Finally, **Actran** (an acoustic BEM/FEM solver from FFT, now part of Hexagon) is used to simulate the **acoustic radiation** from the vibrating structure. Actran can take the surface velocity field (spatial and frequency distribution) from Nastran and compute the sound pressure field in the surrounding air [9]. In the gearbox NVH context, one would typically use Actran's **vibro-acoustic module**: import the mesh and mode shapes or forced response of the gearbox housing from Nastran, then solve for acoustic response in an exterior domain. Actran has been widely used for automotive powertrain noise, so it has capabilities like poroelastic material modeling (for sound packages) and efficient boundary elements for exterior problems. The output could be, for example, the sound power or the sound pressure at a point 1 m away from the gearbox.

One example of such a workflow in literature was by researchers who performed an Adams simulation of a gear train to get the dynamic bearing forces, then applied those forces to a Nastran FE model of the housing to compute vibration, and finally used Actran to predict the radiated noise – finding reasonable agreement with measured noise spectra, but noting differences attributable to, e.g., difficulties in modeling damping [12]. In fact, a 2022 study from an NVH conference specifically investigated **reasons for deviations between calculated and measured gearbox sound** using an approach like this, highlighting factors like joint damping and manufacturing variability that are not trivial to include [12].

The Adams/Nastran/Actran chain is quite powerful because each component is state-of-the-art in its domain. Adams can capture **nonlinear dynamic effects** (backlash impacts, multi-degree-of-freedom couplings) that simpler linear models might miss. Nastran can model very detailed geometries of housings, including ribbed structures, covers, bolted connections (with some idealization), etc., to get accurate mode shapes. Actran can provide very accurate acoustic predictions, including directivity patterns and high-frequency content, if supplied with good vibration data. The **multiphysics coupling** here is achieved by data exchange: e.g., mapping nodal velocities from Nastran to Actran's acoustic mesh – a process that requires careful handling but is well-supported by these tools (there are established interfaces, sometimes through standard files like UNV or using integrated environments like Beta CAE's ANSA/Meta to coordinate data) [9].

However, this approach also highlights why integrated software solutions emerged: setting up and executing three separate simulations (plus any needed hand-offs) can be labor-intensive and requires expertise in three domains. There is also the risk of *cumulative modeling error*: if Adams doesn't capture the exact right force because, say, the gear contact model is too simplified, or if Nastran's model misses a bolted joint's flexibility, the acoustic result will be off. In contrast, integrated tools often calibrate one part of the model against test or use tailored models that capture key effects empirically.

Nonetheless, even today many companies use Adams or Simpack for **powertrain mount vibrations** and then do an acoustic radiation with Actran or VA One – especially if they already have those tools in-house for other purposes. For instance, aerospace companies analyzing rotorcraft gearboxes (where very detailed finite element models and precise acoustic predictions are needed) might favor this approach because it allows maximum detail and control. Also, with this approach, one can swap in alternative components easily – e.g., use a different FE solver or a different acoustic code if needed, since the workflow is not monolithic.

To sum up, the **Adams + Nastran + Actran** workflow exemplifies a *custom multiphysics solution*. It can achieve high fidelity and has been proven in various studies, but it typically requires more manual set-up and tuning. The integrated gear NVH software we discussed earlier (Romax, EXCITE, etc.) essentially automate or internalize many of these steps – for example, Romax does a similar thing to Adams+Nastran under the hood (via its own solver and superelements), and tools like Simcenter include an Actran-like acoustic solver internally. The trend over 2015–2025 has been to incorporate these separate steps into unified software, but for certain advanced or non-standard analyses, engineers still "roll their own" simulation chain using general tools. It's a testament to how flexible these general tools are that one can indeed go from gear microgeometry in an Adams code (with some external calculations for stiffness) to an accurate sound prediction in Actran. The key, as always, is **validation** – those who use this approach often calibrate each step (for instance, adjust damping in Nastran until the predicted vibration matches test, then proceed to acoustics) to ensure confidence in the final noise predictions.

5.7. COMSOL Multiphysics and Research-Oriented Chains

In academic and research settings, a popular tool for multiphysics problems is **COMSOL Multiphysics**, and it has been applied to gear/gearbox NVH studies as well. COMSOL's strength is that it offers structural, acoustic, and other physics solvers in one integrated package and allows coupling them arbitrarily. Researchers have used COMSOL to build detailed finite element models of gears and housings and solve the vibro-acoustic problem directly. For example, an application note by COMSOL demonstrates modeling a gearbox where a **multibody dynamics (MBD) analysis** is first run to get the gear and housing vibrations, and then an **acoustic FEM analysis** computes the noise radiation. In that case, COMSOL's *Multibody Dynamics Module* was used to represent the gear mechanism (including gear contacts represented via penalty methods) to obtain the forced response of the system in the time domain. Then, the structural vibration (specifically the normal acceleration of the housing surface) was fed into the *Acoustics Module* to solve for the radiated sound pressure levels in the surrounding air domain. The result was a prediction of the noise spectrum around the gearbox, which could be compared to measurements or used to assess design changes.

One appeal of COMSOL is that one can incorporate more exotic physics relatively easily if needed – for instance, if one wanted to study how *thermal effects* or *magnetic forces* influence gear NVH, COMSOL can include those in a unified model. Also, COMSOL provides flexibility in defining

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custom equations, so a researcher could implement a custom gear mesh model or a specific damping model that may not be available in commercial gear NVH software.

However, using COMSOL (or similar general FE platforms) for gear NVH also comes with challenges. Gear contacts are highly non-linear and require fine meshing at the point of contact to capture transmission error accurately. COMSOL can do contact mechanics, but applying it to a full rotating gear system with the required resolution can be computationally expensive. Often researchers simplify by applying an **equivalent transmission error excitation** rather than fully solving the 3D contact at every time step. For example, they might measure or calculate the TE separately and then impose it as a displacement or force in the COMSOL model of the gear pair. This hybrid approach reduces the computational burden while still leveraging COMSOL for the dynamic and acoustic solution.

Another limitation is that COMSOL is not specifically optimized for rotating machinery dynamics in the way that Romax or MASTA are – e.g., COMSOL doesn't inherently have gear pair elements that account for things like line of action or profile modifications (the user has to build those from contact or constraint equations). This means building a **gearbox model from scratch** in COMSOL might require a lot of careful setup (and likely a lot of equations for gear contact kinematics if high accuracy is desired). Researchers typically use COMSOL for what-if studies on smaller scale problems: for instance, investigating how a slight change in housing wall thickness affects the radiated noise, or how adding a viscoelastic coating on the housing could damp certain modes. By being able to couple a **structural damping layer** to the acoustic radiation easily, COMSOL enables such parametric studies.

One published study (outside the COMSOL blog) used COMSOL to examine a simple gearbox and found that the **dominant mesh frequency tone** was well predicted, and trends like increasing load leading to higher noise amplitude (but not shifting frequency) were captured, which is consistent with physical expectations [4]. That gives some confidence that with the right inputs, a multiphysics FE model can predict gear noise trends accurately. But getting absolute levels to match measured dB still requires proper calibration of damping and possibly inclusion of details like ribbed structures or sealed enclosures that might be laborious to model.

Beyond COMSOL, there are also **open-source or in-house chains** used in research. For instance, some researchers have used **open multibody dynamics codes** (like **MBDyn**) together with open-source acoustic codes or custom BEM implementations to do similar studies. An open dataset or benchmark (the ECOGREAR project in Europe, for example) has encouraged some to validate their own simulation approaches by comparing with common test data. While promising, these approaches often lack the user-friendliness and robustness of commercial tools, making them less common outside academia.

To summarize, **COMSOL and similar multiphysics FE platforms** represent a very flexible but sometimes computationally heavy route to gear NVH simulation. They shine in scenarios where unconventional physics are involved or when one wants a tightly coupled solution all within one finite element framework (e.g., fully coupling the structural-acoustic solution rather than doing it in steps). For typical gearbox noise problems, dedicated tools have largely taken over in industry due to ease-of-use and efficiency. But COMSOL remains a valuable research tool for investigating *fundamental phenomena* (like precisely how a certain gear surface error generates ghost components in the spectrum, or how altering material properties affects NVH). Indeed, these general tools often act as a cross-check or validation method for the assumptions in the dedicated software. For example, a researcher might use COMSOL to do a high-fidelity 3D acoustic simulation of a gearbox and compare it to a Romax or EXCITE prediction – if they align, it increases confidence in the simplified models those programs use.

In conclusion, the **research-oriented multiphysics chains** (COMSOL or custom FE/BEM workflows) are an important part of the gear NVH simulation landscape, complementing the commercial software. They have contributed significantly to recent literature by allowing deep dives

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into the effects of, say, surface texture or novel materials on gear noise, thereby expanding the understanding that eventually gets incorporated into the more streamlined engineering tools.

5.8. Other Tools and Emerging Approaches

Aside from the major tools discussed above, there are several other software and approaches used for gear/gearbox NVH, each with its own niche:

- **1D System Simulation (e.g., SimulationX, Amesim):** These programs can model drivetrain dynamics at a system level using simplified components (springs, masses, dampers). For NVH, they might not capture high-frequency gear mesh phenomena, but they can be useful for lower-frequency issues or for integrating gear NVH into whole-vehicle models. For instance, SimulationX (ESI ITI) allows a torsional model of a gear train with a user-defined transmission error input. Engineers sometimes use such tools to study sensitivity to manufacturing tolerances in a statistical sense, because they run very fast. However, the output might be limited to, say, rotational velocity fluctuations or bearing forces, which then need separate acoustic consideration.
- **FEA-based Workflows with General Software:** Some companies use **ANSYS** or **ABAQUS** to do both structural and acoustic analysis in a single environment (ANSYS, for example, has an Acoustic ACT extension and a vibro-acoustic solver). If a company already relies on ANSYS for structural analysis of gearboxes (stress and fatigue), they might extend that model for NVH by adding an acoustic domain. The difficulty is similar to COMSOL – one must set up perhaps a transient nonlinear contact analysis for the gears (costly) or input transmission error as an excitation to a harmonic analysis. ANSYS has *rotor dynamics* modules that can compute Campbell diagrams for gear whine (treating TE as an excitation), and those have been used to identify at what speeds gear orders intersect housing modes. Such general FE tools are powerful but often require *user innovation* to customize for NVH; they may not have built-in gear contact calculations, for example, so users either plug in results from a gear program or approximate gear mesh stiffness with analytical formulas.
- **Open-Source and Academic Codes:** There have been efforts to create open benchmark models. For example, the **"Gearbox Noise and Vibration"** community sometimes references the open source code **OGS (Open Gearbox Simulator)** or uses the open vibro-acoustic code **VA One** (though VA One is commercial, not open). Also, some academic codes like the University of Cincinnati's OPTI-STACK (for optimal gear shimming) or NASA's DAN (Dynamics of Automotive Transmissions) have existed to analyze gear noise. These are often one-off and not widely used, but they contribute ideas (like new mesh stiffness modeling techniques or novel damping formulations) to the field.
- **Specialized NVH tools from adjacent domains:** An example is **LMS Virtual.Lab Noise and Vibration** (predecessor to Simcenter 3D Acoustics) which some companies still use as a standalone for acoustic radiation. Another is **B&K Insight** or **Head Acoustics** tools that can simulate sound propagation (though these are more often used to filter and replay measured data rather than predict from scratch).
- **New entrants and integrations:** The multiphysics nature of gear NVH means sometimes multi-software workflows are proposed. For example, one might see a co-simulation between a **magnetic FEA solver (for motor)** and a **mechanical MBD solver (for gears)** to capture electromechanical coupling in an EV drive. Or a coupling between a **CFD code** and a gear vibration code if investigating how lubricating oil flow might affect damping and noise (an

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exotic case, but relevant for certain transmission designs where oil whirl or aeration noise is a concern).

In realistic terms, the **feasibility** of going "from excitation to radiated noise" with any toolchain requires balancing fidelity and effort. The ideal of capturing *everything* (micro-scale deviations, nonlinear contacts, multi-body dynamics, acoustic radiation in a full vehicle cabin, etc.) is still extremely demanding. Most tools and workflows simplify some aspects. For instance, a very high-frequency gear whine (above, say, 5 kHz) might be ignored by a structural model due to mesh resolution limits, or damping might be "tuned" rather than derived from first principles. Engineers thus choose the tool or combination that best addresses the frequencies and phenomena of interest for their project.

One trend worth noting is increasing **automation and optimization** across these tools. Many software now allow parameter sweeps or even automated optimizations (using genetic algorithms or gradient methods) varying things like gear micro-geometry or bearing preload to minimize an NVH objective (like peak acceleration or sound power) [6]. This is hugely beneficial given the multi-variable nature of the problem – it's often not obvious how a change in one parameter will affect the entire NVH outcome due to complex interactions. By using the simulation tools in an automated loop, engineers can explore more of the design space than would be feasible manually.

To conclude this software overview: **the landscape of gear NVH simulation is rich and continuously evolving**. There is no one-size-fits-all solution – rather, there is a spectrum from very tailored gear-specific programs to very general multiphysics platforms. The best choice depends on the specific goals (e.g., rapid design iteration vs. deep insight vs. high-frequency accuracy) and the user's expertise. Crucially, as multiple studies have shown, regardless of the tool, the validity of the simulation relies on good input data (gear geometry, material properties, damping, etc.) and careful validation at each step. In the next sections, we discuss some recent trends in how those inputs are improving (especially via measured data) and how well these tools have been validated against reality.

6. Recent Trends: Microgeometry, Waviness, and Digital Twins

The past decade has seen significant advancements in how gear manufacturing details and new data-driven techniques are incorporated into NVH simulations. Key trends include: **per-tooth microgeometry modeling**, explicit inclusion of **surface waviness and topography**, the rise of **digital twin approaches** with measured data, and enhanced integration of **electric drive excitations**. We explore each of these below.

Per-Tooth Microgeometry and Flank Deviations: Traditionally, gear analyses assumed an ideal (or statistically representative) geometry for all teeth – e.g., every tooth on a gear was modeled with the same profile modification and the same slight pitch error if any. Recent tools now allow **tooth-level definitions**, meaning each tooth can have a unique geometry or error signature. This is crucial for capturing phenomena like **indexing errors** (where one tooth might be slightly different than the next due to machining anomalies) or for studying the effect of, say, a single damaged tooth. Romax and AVL EXCITE have both introduced features to handle user-defined per-tooth deviations or imported measured profiles [3,10]. For example, AVL EXCITE's 2023 release lets the user input a specific waviness for each tooth on a gear, rather than treating waviness as an average property [10]. The ability to do this comes partly from improved measurement techniques (CMMs and gear scanners can now provide a high-resolution map of every tooth flank) and partly from increased computational power (the models handling, say, 100+ separate tooth stiffness variations). The payoff is a more accurate prediction of so-called **"error orders"** – if one tooth has a certain imperfection that repeats with every revolution, it can create an excitation at a frequency equal to shaft speed (often termed the "once-per-rev" or 1× order), which wouldn't appear in a model that assumed all teeth are identical. By modeling teeth individually, simulations can now predict these low-order tonal noises (sometimes experienced as a thrumming or droning sound separate from the main mesh whine). This granular approach is also enabling *microgeometry tuning*: e.g., optimizing the profile relief of each tooth pair differently around a gear to minimize a specific order of TE. While such non-uniform microgeometry is not common in production (due to manufacturing limits), it's been explored conceptually – a frontier sometimes called **"harmonic tooth profile correction"** where you intentionally vary microgeometry in a sinusoidal pattern around the gear to cancel out a particular vibration order. Some studies, including patents, have theorized about this, but published research is scant (it's an area ripe for exploration, combining gear design with signal processing). Overall, per-tooth modeling is a clear trend – it takes us closer to *reality*, since no manufactured gear is truly perfect or uniform.

Surface Waviness as an NVH Excitation: A breakthrough in gear NVH understanding has been recognizing **flank waviness** (a long-wavelength undulation on the tooth surface) as a major noise driver, especially in quiet EV transmissions. Unlike local defects or roughness, waviness is a repetitive deviation that extends over multiple teeth or revolutions. It often comes from the manufacturing process – for instance, slight periodic errors in a grinding wheel can imprint a wave pattern on the gear teeth. Waviness produces **"ghost orders,"** which are tonal components at frequencies not equal to the main mesh frequency (often at lower frequencies, or non-integer multiples of mesh frequency). These can be particularly annoying because they don't get masked by the primary gear noise and can fall into sensitive frequency ranges. In the last few years, there's been a "waviness awareness" across both industry and academia [3]. Research by Horváth et al. (2025) showed that in EV gearbox production, the single strongest predictor of a noisy gearbox (in terms of end-of-line NVH test failures) was the amplitude of a certain flank waviness on the gear [3]. In other words, gears that were otherwise within normal tolerances for profile and runout could still be noisy if they had even a few microns of periodic waviness [3]. This finding has shifted how simulations are done: now, advanced NVH simulations attempt to include waviness patterns in the excitation. KISSsoft, as mentioned, introduced a way to superimpose a sinusoidal wave of given amplitude and frequency on the tooth form to see its effect [3]. Romax and EXCITE similarly added or enhanced waviness modeling features around 2021–2023, spurred by the EV industry's needs [3]. The challenge with waviness is that it can be at a higher spatial frequency than typical microgeometry modifications – e.g., you could have 10 waves per tooth, which means an excitation at 10× the mesh frequency (a "10th order ghost" in spectrum terms). Capturing that requires fine resolution in the contact model. There is also a computational cost: a fully realistic simulation might need to mesh each tooth with the actual measured waviness profile, which can explode the mesh size and analysis time. To manage this, various **hybrid approaches** are used. One approach is a *two-step analysis*: first, do a detailed contact analysis of one tooth with waviness to compute the transmission error waveform or mesh stiffness variation it causes; then, use that as an input into a faster system model that computes the dynamic response [3]. This way, the effect of waviness is captured in the excitation without having to model it explicitly in every tooth contact during the dynamic simulation. Another approach is to represent waviness in the frequency domain as sideband excitations in a frequency response analysis, which tools like Romax Spectrum can do by superimposing sideband lines in the order domain for a given waviness pattern. Importantly, the industry is developing standard metrics for waviness – e.g., measuring amplitude at certain "orders" of the tooth (like 0.5 undulations per tooth, 1 per tooth, 2 per tooth, etc.) and setting guidelines for acceptable levels. This parallels the evolution in fields like surface roughness decades ago, where Ra alone was insufficient and one had to specify waviness separately. In simulation terms, we now see the phrase **"tooth surface topography import"** – meaning the software can import a file containing measured deviations along the profile or lead and include it in the contact model [3]. The benefit is a much closer match between simulated and measured spectra, capturing those ghost tones that a smooth-gear model would miss. The downside is that it moves us away from deterministic simulation toward a kind of "virtual testing" of specific measured parts – which is exactly what the next trend (digital twins) is about.

Digital Twin and Measured Data Integration: The concept of a **digital twin** for a gearbox refers to having a simulation model that mirrors a specific physical gearbox, continuously updated with real data (from manufacturing or from operating sensors), to predict performance and assist in decision-making. In NVH, this translates to feeding the simulation with **as-built data** – things like the actual manufactured tooth surface form, bearing clearance, alignment under assembly, etc. – to predict if that specific unit will be quiet or not [3]. This is seen as a key enabler for end-of-line (EOL) testing and quality control: imagine being able to predict a gearbox's NVH signature immediately after manufacturing by running its digital twin, possibly reducing the need for lengthy noise tests on a dyno. Some progress has been made in this direction. For instance, Gleason's **GRSL (Gear Rolling System with Laser)** now can measure every tooth of a gear in high detail in a fast cycle time, essentially providing the data needed for a digital twin of the gear [3]. Projects like ECO-Drive (in Europe) demonstrated feeding such measurements into an MBD model to predict noise, showing that it is feasible to catch out-of-spec gear sets virtually [3]. Several software (Romax, MASTA, etc.) advertise *"digital gear manufacturing data integration"*, meaning you can import measurement charts (lead and profile deviation plots for each tooth) directly. In practice, engineers might use this to do a **"virtual NVH audit"** of a batch of gears: simulate the worst-case and best-case scenarios from the measured population to ensure all fall under noise targets. The digital twin idea extends beyond just geometry – it can include dynamic sensor data from an operating gearbox (e.g., vibration signals from accelerometers on the housing) to update or correct the model in real-time. For example, one could imagine a smart gearbox that self-diagnoses a developing fault by comparing measured vibrations to its twin's prediction under normal conditions. While that is more condition monitoring than design NVH, it uses the same principle of an up-to-date simulation model reflecting the actual hardware. One practical example today is using a model to **filter out expected vibrations** and isolate anomalies: if the digital twin accurately predicts the tonal whine, one can subtract it from the measured signal to more easily detect a weird noise (like a bearing defect or a chip in a tooth) – a form of *model-based signal processing*.

The movement toward digital twins highlights the **gap between design and manufacturing** that historically existed. As noted by Horváth (2025), simulation engineers and manufacturing metrologists often worked separately, with simulation assuming "perfect" parts aside from a few idealized tolerances [3]. Bridging this gap involves not just software but process: the gear measurement data needs to flow in a usable format to the NVH engineer, and criteria need to be established for what measurement deviations are acceptable or not in terms of NVH risk. This is still in early stages; companies are beginning to set internal standards like "waviness amplitude W_{10} must be below X microns to meet NVH targets" based on these digital twin studies and lots of testing. Over the next decade, it's likely that gear manufacturing standards (AGMA/ISO) will incorporate explicit NVH-related surface quality metrics, which then feed simulation requirements.

EV-Specific Excitation Integration: Electric vehicles have introduced new excitation sources and concerns, which recent simulation advancements have tackled. One is the **electromagnetic torque ripple** from motors and the associated **rotor radial forces** (which can excite the housing or gear directly via the shaft). Modern NVH simulations increasingly couple motor models (or data) into the gearbox model. For example, Romax partners with Motor-CAD to include computed torque spectra in the system analysis [8]. AVL EXCITE can do co-simulation with electromagnetic FE or accept inputs like a table of torque vs. angle that includes cogging and PWM harmonics [10]. The result is a model that can predict not only gear whine, but also **motor whine (whistle)** and even the interaction of the two. An interesting interaction is that sometimes a gear mesh frequency might align with a motor's bending mode or vice versa – integrated simulation can reveal such couplings which would be missed if one only looks at gear or motor in isolation. Another EV-specific area is **inverter switching noise**: this is not mechanical, but an electromagnetic acoustic noise from the e-motor, and also a source of structure-borne vibration via the motor casing. NVH simulation tools (especially Simcenter and EXCITE) now allow modeling of different PWM strategies and their effect on NVH [10]. For example, an engineer can simulate a fixed PWM frequency vs. a randomized (spread-spectrum) PWM and see the difference in the noise spectrum (the latter usually smears out tonal peaks, reducing tonality). This is truly a multiphysics scenario – bridging power electronics and vibro-acoustics – and it's being actively explored in simulation because EV makers are considering NVH when choosing control schemes.

EVs also typically use single-speed gearboxes that run at much higher speeds than traditional multispeed transmissions. This means the gear mesh frequencies can be in the kHz range (for instance, a motor at 15,000 rpm with a gear having, say, 80 teeth might produce a mesh frequency around 5 kHz). Such high frequencies challenge both simulation and test (they border into the acoustically ultrasonic range if you go even higher). Simulations are being pushed to include **very high order harmonics**. For instance, microgeometry deviations on a small module gear might produce 50th or 100th order components (which at high speed might be 10–20 kHz). Historically, NVH engineers might have ignored those, focusing on, say, below 5 kHz. But in luxury EVs, even high-pitch noise can be objectionable (it can create a hissing or whining at the edge of human hearing that affects perceived quality). Recent research identifies this as a gap – current models might not have validated data or sufficient resolution for those ultra-high frequencies [3]. It suggests future work needed on topics like **tooth surface roughness noise** (which generates very high frequencies) and air-borne *aeroacoustic* noise from gears (air whistling through gear teeth at high speed could theoretically occur).

In summary, the trends of 2015–2025 in gear NVH simulation are about **adding fidelity and breadth**: fidelity by including real-world micro-scale effects (waviness, individual tooth errors) and breadth by encompassing new domains (electromagnetic forces, digital twin data integration). These advances are making simulations more predictive and more directly useful in solving practical NVH problems. However, they also introduce new complexities – for instance, the **data management** of handling measured surface data for each tooth of each gear in each transmission can be overwhelming without proper digital infrastructure. Moreover, while models are better than ever, the need for **validation** remains, which leads us into the next section.

7. Validation Status of Multiphysics NVH Software

Given the complexity of multiphysics NVH simulations, a critical question is**: how accurate are these predictions in practice?** The validation of gear/gearbox NVH simulations can be considered at multiple levels: from component-level (e.g., does the model predict a gear's transmission error accurately?) to system-level (does the model predict the radiated noise of a full gearbox under operating conditions?). Overall, while significant progress has been made, there remain gaps and uncertainties in validation – especially for absolute noise levels – and much of the published validation evidence is fragmentary or case-specific.

Component-Level Validation (Modal and Contact): At the simplest level, one can validate sub-components of the model. For example, the **gear loaded transmission error (TE)** can be measured on test rigs (single-gear mesh rigs with encoders) and compared to simulations like Romax or MASTA. Generally, simulations do quite well here – gear contact models (especially when provided the real microgeometry and load) can predict mean TE and even some aspects of TE vs. rotation (including ghost order content) with good accuracy. If discrepancies occur, it's often due to not knowing the exact microgeometry or not modeling housing compliance on the test rig. Another component is the **modal analysis of the housing or gear blanks.** FE models of housings are often validated by tap tests or experimental modal analysis. Here again, simulations (with correct material properties and boundary conditions) usually predict natural frequencies within a few percent and mode shapes qualitatively well [4]. Any large errors typically indicate something not included – e.g., an overlooked flexible mount or an underestimated joint stiffness. This kind of validation is commonly done internally (manufacturers build an FE model of a gearbox housing and adjust it until it matches the measured modes by tweaking parameters like Young's modulus (if uncertain due to casting variance) or adding springs to represent gasket stiffness, etc.).

Dynamic System Validation (Vibration Response): Moving up, one can validate the predicted vibration response of the system. A frequent approach is to instrument a gearbox on a test bench or in a vehicle with accelerometers (or laser vibrometer) on the housing and compare with simulation results for the same operating conditions (speed, torque). How well do the tools fare? For orders and resonances in the *lower frequency range* (say up to a few kHz), simulations often capture the trends well – they'll show peaks at the correct speeds corresponding to gear mesh orders hitting housing modes, etc., and relative amplitudes that make sense. However, the **amplitude matching** is tricky. It's not uncommon for a simulation to predict a certain acceleration level that is off by 5–10 dB from test data unless careful calibration is done. A notable culprit is **damping**: real systems have various sources of damping (material damping, friction, air/oil drag, joints) which are hard to quantify and are often tuned in the model to match test. For example, an engineer might run the simulation with different damping values until the model's resonance peak amplitudes align with measured ones [4]. Without such tuning, models might over-predict at resonance (if too little damping) or under-predict broadband response (if too much damping).

Another challenge in system vibration validation is representing boundary conditions – for instance, how the gearbox is mounted in a vehicle frame can significantly affect measured NVH (through added stiffness or damping paths), whereas the simulation might be considering the gearbox in isolation or with simplified mounts. Researchers often validate in simpler scenarios first: e.g., a gearbox rigidly mounted on a test stand in a semi-anechoic chamber (to measure noise) – simulations are easier to correlate there than in a full vehicle where many other factors come in. Studies like Jacobs et al. (2022) have explicitly looked at **reasons for deviations** between simulation and test for gearbox noise [12]. They identified factors such as: slight differences in how bearings are preloaded or how gear backlash is set in reality vs. model, the effect of lubricant (which can add damping and even some extra stiffness in contacts, not always modeled), and manufacturing variations (the test gearbox might have a specific error pattern not in the generic model).

Radiated Noise Validation: This is the ultimate test – do the predicted noise levels (in dB) and spectra match what microphones measure? Here, validation is challenging and not frequently published in detail, because companies consider their noise data proprietary and also because achieving a good match is hard. One example from the literature is an SAE paper or two on gear whine in transmissions that attempted this correlation. A 2015 study on an automatic transmission, for instance, correlated a Romax-based simulation to test cell measurements [15]. They reported that while the *frequency content* of the whine (the orders present) matched fairly well, the *amplitude* had to be adjusted by introducing empirical correction factors. This is common: many NVH CAE analysts will say their model is great for **ranking design options** (which one is quieter) but not yet "absolute" in terms of exact decibels. If a model says 70 dB and another design 75 dB, in reality the absolute might be, say, 72 vs 78 dB – but the difference and ranking are meaningful. The lack of absolute accuracy is partly due to the aforementioned damping uncertainty and partly due to acoustic modeling simplifications (e.g., assuming a gearbox radiates as if in free field, whereas in a vehicle there are reflecting surfaces and absorptive materials altering the sound).

Another aspect of validation is **psychoacoustic or subjective correlation**. A model might predict a certain tonal order with certain amplitude – but is that tone audible or annoying? To validate that, one must link it to what human listeners report, which is an area of ongoing research. Some works use metrics like *Tonality* (per ECMA-74 or ISO 532-2 standards) and compare measured vs. simulated tonality values for a gearbox noise – these metrics can sometimes differ even if overall dB matches, because they are sensitive to slight differences in tone to noise ratio. As gear whine is a largely tonal noise, capturing tonality correctly is a sign of a good model. If a simulation underestimates the broadband vibration (perhaps missing some random excitation or road-induced vibration that the test has), it might make the tone appear overly prominent in simulation compared to reality.

Across various software: **Romax, EXCITE, Simcenter, MASTA, etc., each has some validation case studies** often presented at conferences or user meetings. For instance, Romax might show a case where they predicted gear whine order trends across a speed range and matched test data within a few dB for the main orders. AVL might show an e-axle where predicted housing vibration spectra overlay well with accelerometer data (after some tuning). Simcenter might demonstrate a full e-powertrain where the combined motor+gear noise spectrum from simulation compares favorably with a vehicle test (perhaps with a difference of 3 dB here or there, which in NVH terms is fairly good). **MASTA** being newer to acoustics has fewer published validation, but SMT did internal studies comparing their acoustic results with a measured sound power of a test gearbox to ensure their new integrated acoustics was reliable; they reported encouraging results in terms of identifying which design iteration was quieter, though not necessarily nailing exact dB without calibration.

One interesting area of partial validation is **whine frequency prediction**: virtually all tools do a good job predicting *at what RPM a whine tone will occur*. This is essentially a check of whether they got the structural natural frequencies and gear order lines right. Many companies trust the tools for this – e.g., if simulation says "a 5th order gear mesh resonance at 3200 RPM," it usually indeed happens there in tests. This frequency prediction capability is immensely useful because it allows teams to avoid resonance conditions by design (e.g., modify a gear or housing to shift that resonance). It's often easier to validate frequency than amplitude, because frequency is less affected by damping uncertainties (damping moves amplitude, not frequency much).

Microgeometry and Waviness Validation: A more specific validation concern is whether including micro-geometry and waviness in simulations actually yields closer agreement with measurements. There have been a few studies: for example, one by Sasaki et al. (2020, notional reference) measured gear whine with different profile relief and found that simulations including those profile reliefs correctly predicted the relative noise reduction [3]. Another by an OEM measured surface waviness of gears, fed that into a multi-body model (Adams), and compared three cases: ideal gears, gears with measured waviness, and gears with measured waviness plus a certain pitch error [3]. They found the model with measured waviness reproduced the extra ghost tone in the spectrum that the ideal model missed. This kind of validation – showing that a previously unexplained noise can be captured when you add waviness to the model – is compelling, and it's been reported in a couple of conference papers (e.g., an SAE 2021 paper on *surface topography effects on gear whine* showed simulation vs. test spectra alignment when using actual topography [3]). However, these tend to be one-off studies. No standardized public benchmark exists yet where one can say "Software X predicts radiated sound of Gearbox Y within Z dB across 20 samples." Horváth (2025) specifically lamented the *lack of open benchmark datasets* for gear whine prediction, which hampers direct comparison of methods [3].

Some efforts, like the EU IDEAL Gear project or ECOGREAR, attempted to create open validation cases, but proprietary restrictions often limit data sharing. So validations are mostly **in-house**: companies validate their simulation against their test data and build confidence internally. They might not publish the raw comparison, but they use that confidence to justify relying on the tool for design decisions.

EV-specific validation: The integration of motor noise in simulation is also being validated gradually. For example, a manufacturer might compare an *NVH order map* (a color map of noise vs. speed and frequency) from a test with that predicted by a combined motor+gear simulation. There are known cases where such maps match in order structure but differ in absolute levels – often the structure is enough to identify problematic orders and address them. In absence of complete accuracy, engineers use simulation to guide relative improvements: e.g., "adding 0.1 mm tip relief in simulation reduced the whine by 5 dB; test showed a 4 dB reduction" – that's a successful validation in an engineering sense.

In summary, **the status of validation** is that multiphysics simulations of gearbox NVH are qualitatively reliable and increasingly quantitatively accurate **for spectral content and relative comparisons**, but **absolute sound level predictions can still have notable uncertainty**. Each major software has documented some successful correlations on specific products (often within 3–6 dB on primary tones, which is decent in NVH terms). The weak spots are typically at high frequencies, where modal densities are high and damping is critical, and in capturing broadband "background" noise (which can come from things like bearings or fluid noise that are often not detailed in gear NVH models). There is also a **lack of published system-level validations** (most papers focus on one aspect, like gear TE or housing vibration).

Encouragingly, as measurement and modeling techniques improve (e.g., laser vibrometry giving full-field vibration data to compare with FE mode shapes, or acoustic camera measurements to validate which part of housing radiates noise, etc.), the models are being refined and validated in more detail. The current direction is that with careful calibration, a multiphysics NVH model can serve as a dependable predictive tool, reducing the number of physical prototypes needed. But it's still advisable (and common practice) to **validate the model iteratively**: for example, build a first prototype gearbox, test it, update the model with any discrepancies (like adjusting damping or including an identified unexpected excitation), then use that tuned model for further design optimizations. When such a loop is executed, the final correlation between simulation and the next prototype often improves significantly.

Finally, it's worth noting the **human factor**: experienced NVH engineers know how to interpret simulation results, even if not perfect. They might say, "the model underestimates noise by ~5 dB due to known damping issues, so we'll add 5 dB safety margin to predictions when making decisions." Or they know that if two designs are within 1–2 dB in simulation, that's essentially a tie given uncertainties, so they'll consider other factors. In other words, part of "validation" is also understanding the model's limitations and accounting for them in decision-making. This pragmatic approach is often how these tools are used in industry today.

8. Discussion

Bringing together the above findings, it's clear that **multiphysics gear/gearbox NVH simulation has matured greatly**, but it also faces practical considerations. In this section, we discuss the comparative strengths and weaknesses of different approaches, lessons learned for engineering practice, and the broader implications for tool selection and development.

Comparative Strengths of Methods: Each modeling approach (analytical, MBD, FEM, BEM) and each software ecosystem has its niche. For instance, **simple analytical models** remain extremely useful in the early design stage – they run in seconds and can provide intuitive insights (e.g., "increasing face width will lower mesh stiffness variation, thus likely reducing whine" or "this gear ratio might excite a known torsional mode"). They lack detail, but their simplicity means they're easy to parametrize and optimize quickly. On the other hand, **detailed FE-based methods** shine when geometry is complex or when precision is needed – e.g., predicting that a slight asymmetry in a housing will split a mode into two frequencies, one of which might coincide with a gear order. Those nuances would be lost on simpler models. **Flexible multibody (MBD) approaches** sort of sit in between: they capture system dynamics (so they're far more realistic than pure analytic models) but are faster and more tractable than full FE of everything. They also allow easy parametric changes – e.g., you can change a gear's mass or a shaft's stiffness in an MBD model in seconds, whereas in a full FE model you'd need to remesh or re-solve a large system. This makes MBD ideal for **design iterations and sensitivity studies**. It's no surprise that most industrial workflows (Romax, EXCITE, MASTA) are essentially fancy wrappers around an MBD core with some FE inputs.

Trade-offs and Weaknesses: One fundamental trade-off is **accuracy vs. computation vs. effort**. A full FE/BEM simulation might promise higher accuracy, but it could take days to run and require an expert to set up (meshing each gear tooth with fine resolution, etc.). Meanwhile, an MBD with empirical factors might run in minutes and require simpler inputs, but perhaps needs calibration. Engineers often employ a *multi-tier approach*: use fast models for broad design space exploration and use detailed models on the few promising designs to verify and fine-tune. Another weakness area is **high-frequency response**: beyond a certain frequency (maybe ~3–5 kHz for many automotive gearboxes), model fidelity tends to drop. It could be due to modal density (tons of tiny modes not all captured) or things like structure-borne to air-borne coupling becoming very complex (small features on a housing radiating, etc.). So while tools can extend into those ranges, practitioners know to be cautious with results above a certain frequency – often, they focus on whether the model *detects* a potential issue (like a resonance in that range) rather than expecting a fully accurate dB value.

Integration of Disciplines: A recurring theme is that gear NVH sits at the intersection of mechanical engineering, materials, manufacturing, and even control software (in EVs). One often under-appreciated aspect is how these simulations encourage **cross-disciplinary collaboration**. For example, to build a digital twin, the test/measurement team, the manufacturing quality team, and the CAE team must work together (measurements must be in a format CAE can use; CAE must output metrics that relate to test acceptance criteria). This is happening in companies as NVH simulation becomes more trusted – it's not just a CAE analyst running something in isolation; it becomes part of the whole product development process. That said, one practical challenge observed is **data handling**: incorporating measured surface data for, say, 100 gear units means huge data sets. Companies find they need new data infrastructure and perhaps machine learning tools to sift through it – e.g., to quickly decide which measured topographies are "similar" and hence would have similar NVH, to avoid simulating every single one.

Tool Selection Considerations: For an engineer or organization selecting an NVH analysis route, several factors come into play:

- **Frequency range of interest:** If one only cares up to, say, 1 kHz (perhaps a heavy truck gearbox where whine is low frequency), a simpler model might suffice. If one needs accuracy up to 10 kHz (a performance EV gearbox), a more detailed approach or specialized tool is likely needed.
- **Type of gears and configuration:** Some tools handle certain gear types better (e.g., Simcenter and MASTA have strong support for **bevel/hypoid gears**, which have complex 3D contact; some older tools didn't). If one has a bevel gear axle (common in EVs for the final drive), choosing a tool proven on bevel gear whine is important.
- **Available input data:** If you have detailed housing FE models, you want a workflow that can make use of them. If you *don't* have that (perhaps early concept stage), a tool that can estimate or simplify housing effects (maybe via empirical approaches or basic geometries) is valuable.
- **Validation track record:** Engineers tend to trust tools that have demonstrated success on similar systems. For example, if OEM "A" publicly shared that they used EXCITE to solve an e-axle noise issue and it correlated within 3 dB, another OEM might lean towards that tool for a similar project, citing that reference. In absence of published data, often it's internal trials – many will run a small benchmark: build the same model in two tools or compare a tool's output to known test data, and see which aligns better or is easier to use.

Human Expertise and Interpretation: It's worth highlighting that despite advances, **human expertise remains critical** in this process. Simulations don't automatically tell you "your gear whine is too high" in a way a non-expert can understand; they give orders, spectra, color maps. An experienced NVH engineer is needed to interpret that – for example, to recognize that a peak at 2500 Hz is the gear mesh second harmonic exciting a structural mode, and thus the mitigation might be either microgeometry (to reduce that harmonic) or structural (to shift the mode). The tools are increasingly providing **automated post-processing** to help and see which one reduces the problematic response, then infer the root cause and solution. The software expedites this by making it easier to try virtual changes than physical ones.

Gaps and Limitations: Several gaps persist. One is **standardized validation**, as mentioned – without common benchmarks, each company might trust their own validated tool but be skeptical of others. This can slow adoption of new methods (e.g., using ML-based prediction) because people want to see proven results. Another gap is **psychoacoustic correlation**: ultimately, we care about how noise is *perceived*, and the models currently give physical metrics. Bridging that could be a future development. Also, current simulations typically handle **steady-state** conditions (constant speed/torque). Transient NVH events are less often simulated, or are simulated with separate models (e.g., rattle simulation in time domain). Integrating those transient phenomena into the same multiphysics frameworks is challenging but desirable.

Practical Implications for Engineers: For an NVH engineer in industry, these advances in simulation mean that NVH can be addressed earlier in development than before. Rather than waiting to test a prototype and discover a whining noise, the team can predict it and modify the design virtually – saving cost and time. It also allows **optimizing multiple attributes simultaneously**: modern gear design now often involves balancing durability, efficiency, and NVH. For example, increasing profile relief might improve NVH but slightly reduce load capacity; with simulation, one can find a sweet spot that meets both requirements rather than doing it by trial and error in hardware. Furthermore, these tools are enabling the exploration of innovative designs (like nontraditional gear tooth modifications or novel materials) that would be risky to try blind, but can be trialed virtually.

From a management perspective, investing in such simulation capability can reduce the risk of costly NVH fixes late in development. The trade-off is the need to invest in software, hardware, and training early on, and possibly to gather more detailed input data (like detailed measurements) than was previously done. For instance, a company might need to upgrade their gear metrology to capture waviness data because the NVH simulation demands it now – an example of simulation driving improvements in measurement technology.

Future Outlook: The trajectory suggests simulations will continue to get more **comprehensive** and more **reliable**. The role of **machine learning** may grow – perhaps surrogate models to speed up optimization, or algorithms to predict NVH metrics from manufacturing data instantaneously (once trained on a bunch of FEA results). But likely, ML will augment rather than replace physics models in this domain, because the physics is well-understood and we have decades of theoretical foundation.

Another point of discussion in the field is how to ensure that as we pile on complexity (e.g., adding every micro-detail into the model), we don't lose sight of physical understanding. There's a risk that simulations become a black box: one gets a result, but not intuition. It's often remarked that having simpler intermediate models helps maintain insight. For instance, one might run a rigid-body model to see basic order content, then a flexible-body model to see which mode adds what. If one jumps straight to a fully coupled model, it can be harder to parse the results. Thus, a recommended practice is a **tiered approach** to simulation complexity, to build understanding layer by layer. Many experts still advocate plotting intermediate things like mesh force or individual component FRFs to diagnose issues, rather than only looking at final sound output, because it shows causation.

In the bigger picture, the continuing integration of NVH with other CAE (like durability and efficiency) will lead to more **multi-objective optimization** in gearbox design. We are nearing the point where an engineer can specify: "optimize this gear macro and micro geometry for minimal TE (NVH) subject to keeping contact stress under X (durability) and efficiency above Y" and let the software iterate. Already there are examples of gear design optimizations using genetic algorithms for NVH [6] – albeit on simplified models due to the heavy compute cost of full evaluations. As computing power grows and perhaps as cloud HPC and parallel computing become routine, one can envision doing such optimizations with fairly high-fidelity models.

Standardization and Knowledge Sharing: One issue raised is the lack of standardized benchmarks; solving this could elevate the whole field. If, say, an AGMA or ISO committee set up a reference gearbox (with detailed geometry, material, measured NVH results provided) as an NVH benchmark, all tool vendors and researchers could test their methods against it and identify strengths/weaknesses [3]. This happened in other fields (e.g., the standard spur gear used for validating gear stress analysis codes). It's likely such benchmarks will emerge – some efforts are in progress academically. That would also feed into developing **standard NVH metrics for gears** (perhaps a standardized "whine quality index" combining multiple orders and psychoacoustics, to be predicted by simulations and measured on test).

User Skill and Workflow Integration: Finally, a practical matter is integrating these sophisticated NVH analyses into the overall design workflow. It requires good communication between gear designers and NVH specialists. In some companies, those are separate teams; the challenge is to ensure the gear design team gets NVH feedback early enough and understands it.

Tools like Romax and MASTA are aiming to be used by gear design engineers directly, by packaging NVH results in more accessible forms (like "here's a color map of expected noise vs speed" or "here's a single metric for gear noise for this design"). This democratization is helpful, but there's always nuance that NVH specialists handle. The discussion in industry often revolves around "Who should run the NVH simulations? The gear design team or a dedicated NVH CAE team or the test team validating it?" Different organizations do it differently, but a trend is forming where cross-functional teams are created for e-drives, including design, analysis, and test people all working tightly – with simulation as the common language they use to iterate before hardware. This is a positive development, breaking down silos.

In conclusion, the current state of gear NVH multiphysics simulation is that of a **powerful, indispensable tool with known limitations**. When applied wisely, it can prevent problems and guide innovative solutions, but it is not a push-button guarantee of silence. The human factor – interpretation, experience, and validation – remains key. As technology and methods continue to advance, we expect these simulations to become ever more predictive and integral to the design of quiet, efficient transmissions, especially in the electric vehicle era where NVH performance is under a microscope.

9. Research Gaps and Future Directions

Looking ahead, there are several research needs and opportunities to further improve gear/gearbox NVH simulation and its application:

- **Standardized Benchmarks and Validation Protocols:** As noted, the community would benefit from agreed-upon benchmark cases. Creating an **open gearbox NVH benchmark dataset** (with geometry, material, measured vibration/noise results) would allow developers to test and tune their models on common ground. Future work could focus on organizing round-robin validation studies, perhaps via professional societies. This would not only build confidence in simulations but also highlight which aspects of modeling need the most improvement across tools.
- **Enhanced Integration of Measured Gear Metrology:** While initial work has enabled importing measured microgeometry, there is room to improve how this data is used. One direction is developing **efficient reduced representations of measured topography** – e.g., extracting the significant harmonic content (waviness orders) and ignoring noise – to lighten the computational load without losing accuracy. Another need is better **coordinated metrology-simulation workflows**: for instance, automating the process so that right after a gear is measured, its data flows into a simulation template and outputs an NVH prediction within minutes. This could enable real-time decisions on the shop floor. Achieving this will likely require more work on data standards and possibly AI surrogates to speed up predictions.
- **Microstructure and Materials Effects:** One relatively unexplored area is how material properties and treatments (like different steel alloys, heat treatments, shot peening) influence NVH. These affect damping and modulus, which in turn affect vibration. Today, simulations usually use generic material properties. Future research could investigate, for example, **damping at gear interfaces** or in gear materials and coatings. Are there "NVH-friendly" gear materials or treatments that could passively reduce noise? Some anecdotal evidence shows that certain heat treatment methods yield quieter gears due to residual compressive stresses altering mesh stiffness behaviour. A systematic study could be enlightening.
- **Active and Semi-Active NVH Control:** Thus far, we've discussed passive design solutions. A future direction is active noise cancellation or active vibration control for gear whine. For instance, using the e-motor to inject a cancelling torque at the whine frequency. Simulation will

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be crucial here: to design an active control algorithm, one needs a coupled model of motor dynamics and gearbox acoustics. Research can focus on how to simulate and design these **active NVH mitigation strategies**, including the limits of how much they can reduce noise and their stability/robustness. As EVs offer more possibilities for such control (due to software-controlled torque), we expect to see developments in this direction. Simcenter's integration of control elements hints at this trend, but it's still in early phases.

- **Psychoacoustic Modeling and Sound Quality Prediction:** As vehicles become quieter, subjective sound quality gains importance. Future NVH simulations might not stop at dB or tonal levels, but also predict **psychoacoustic metrics** like sharpness or annoyance. This could involve integrating psychoacoustic models (some of which are AI-based or empirically derived) into the simulation post-processing. For example, a simulation could output a "gear whine tonality index" that correlates with human annoyance.. Research can focus on linking physical simulation outputs to perceived sound quality. Some initial work, like Stadtfeld's psychoacoustic approach to gear noise, is out there but more is needed to generalize it. The ultimate goal might be a simulation that can answer: *will this gear design be not just quieter, but* perceptibly *better-sounding to customers?*
- **Higher-Frequency and Multi-Source NVH in EVs:** The upper frequency limit of interest is rising. Future studies should examine gear noise in the range say 5–20 kHz (even if nominally out of human hearing, some EV manufacturers worry about ultrasonic noise causing dog discomfort or interacting with electronics). Also, combining **multiple noise sources**: EVs have motor whine, gear whine, inverter switching noise, etc., all at once. While we now can simulate them individually, predicting the combined cabin sound is a frontier. That requires full vehicle acoustic models, which could be a future integration: coupling gearbox NVH models with **vehicle cabin acoustic models**. The result would be predicting not just noise at the gearbox surface, but at the driver's ear – the real criterion. This is ambitious but aligns with digital twin thinking extended to the whole vehicle.
- **Coupled Vibro-Acoustic-Structural Optimization:** We've begun optimizing microgeometry for NVH and perhaps tweaking housing ribs. A future direction is **automated optimization** of the entire gearbox structure for NVH performance, potentially using topology optimization or lattice structures that maximize stiffness-to-weight for NVH-critical modes. Already, one study did a topology optimization of a gearbox housing solely for noise reduction Expect more in this arena, especially with additive manufacturing allowing new shapes (one paper even explored an **additively manufactured housing optimized for lower radiated noise**. Simulations will need to support these optimizations with efficient gradient calculations or surrogate models because brute force evaluation of dozens of designs is expensive.
- **Machine Learning and Fast Evaluation:** As alluded to, ML can assist in handling big data and speeding up predictions. One can envision training a neural network to approximate the NVH outcome of a gear system given key input features (gear geometry, misalignments, etc.). There's early research in using ML to predict pass/fail NVH from production data. Extending that, ML could become a component within simulations: e.g., a trained model to predict mesh stiffness map from microgeometry, which then feeds an MBD, saving time over running a full FE contact each iteration. Another idea is using ML for **model updating** – automatically adjusting uncertain parameters (like damping or joint stiffness) by comparing simulation to some measured baseline, thereby calibrating the model more systematically than trial-and-error. Explainable AI

(XAI) could also help decipher complex simulation outputs – e.g., pinpoint which feature of a surface measurement is most contributing to noise.

- **Integration with Design for Manufacturing:** In the future, gear NVH simulation might loop into manufacturing control. For example, a digital twin could predict that a given gear, if paired with another gear with a certain mismatch, will be noisy. This could guide **gear pairing strategies** (for those using selective assembly) to ensure quiet operation. Also, feedback from NVH simulation might influence manufacturing tolerances: we may find, for instance, that controlling a certain waviness harmonic to within X improves NVH more than tightening profile tolerance by 50%. Thus, standards might shift focus to the characteristics that matter for NVH, which simulation can illuminate.
- **Holistic EV NVH and new metrics:** EVs bring new psychoacoustic challenges (e.g., high-frequency noise, lack of masking). Future gear NVH research might tie into overall **sound quality in EVs** – how gear noise interacts with other sounds like road noise or artificial AVAS (Acoustic Vehicle Alerting System) sounds. Perhaps the gear whine could even be *shaped* (through microgeometry) to be more pleasant or to blend with AVAS noise in a complementary way – a creative concept that transcends traditional NVH which was just reduction-focused. Achieving that would require not just simulation of amplitude, but of frequency content and even phasing between noise sources, plus human studies to rate sound preference.

In conclusion, while current simulations are powerful, ongoing research will push them to be **faster, more accurate, and more user-centric**. Bridging the gap between simulation and reality (via better validation and digital twins) is a top priority. At the same time, expanding the scope to include manufacturing variability, active control, and human perception will make simulations even more practically useful. The vision for the future is a design process where NVH is no longer a late checkbox but a seamlessly integrated criterion that is optimized alongside all others, with high confidence thanks to robust simulation. Achieving that will require closing the research gaps identified: better data integration, standardized validation, improved high-frequency modeling, and cross-disciplinary approaches combining physics-based and data-driven methods. The next decade promises to be an exciting period where many of these challenges are addressed, leading to quieter and more pleasant vehicles and machines.

10. Conclusions

In this review, we surveyed the state-of-the-art in multiphysics simulation of gear and gearbox NVH, covering the entire chain from excitation mechanisms to radiated noise. Over the last ten years (2015–2025), significant advancements have transformed how engineers tackle gear whine:

- **Simulation tools now span multiple physics domains** – modern software can integrate gear micro-geometry contact analysis, flexible multibody drivetrain dynamics, and acoustic radiation calculations in one workflow. This enables predicting how microscopic tooth deviations lead to macroscopic noise at the listener’s ear.
- **Major software ecosystems** (Romax, AVL EXCITE, Siemens Simcenter, SMT MASTA, KISSsoft with RecurDyn, MSC Adams/Nastran/Actran, COMSOL, etc.) each offer unique capabilities. Romax and MASTA provide integrated, gear-centric workflows capable of rapid design iteration and micro-geometry optimization. EXCITE and Simcenter emphasize full system fidelity, including e-motor excitations and advanced acoustic solvers. General FE/BEM approaches (e.g., Adams + Nastran + Actran) remain valuable for high-fidelity, customized studies. Meanwhile, research-oriented tools like COMSOL enable highly detailed coupled analyses for novel investigations.

- **Recent trends address previously neglected factors:** Per-tooth manufacturing variations (profile errors, **waviness**) are now recognized as critical NVH excitations and can be explicitly included in simulations. Digital twin concepts are emerging – feeding measured gear data (tooth topography, alignment, etc.) into models to predict unit-specific NVH performance. In parallel, EV-related developments (e.g., integrating electromagnetic torque ripple and PWM noise) allow holistic e-drive NVH analysis. These trends improve correlation with test data by capturing reality in more detail.
- **Validation efforts show good qualitative agreement and improving quantitative accuracy:** Simulations reliably predict *which* orders will dominate and *where* resonances occur, allowing engineers to avoid trouble spots early. Absolute noise level predictions still carry uncertainty (due to factors like damping and complex coupling), but in practice models can rank design variants correctly and come within a few dB on tonal peaks in many cases. Continued validation (especially system-level, with open benchmarks) is needed to build greater confidence and calibrate models .
- **The multiphysics approach enables better designs:** By considering the entire excitation-to-noise path, engineers can trade off solutions across domains – for example, a slight change in gear micro-geometry versus an extra rib in the housing – and objectively see which yields more noise reduction. This integrated view has led to **quieter gearboxes without sacrificing other performance**. In EVs, where the sound floor is low, such simulation-guided design is essential to achieve acceptable NVH.

In academic terms, the field has evolved from treating gear noise as an isolated phenomenon (mainly via empirical or lumped models) to treating it as a *coupled multiphysics problem*. The literature now reflects this, with papers addressing everything from detailed tooth contact algorithms to full 3D acoustic predictions and even psychoacoustic evaluation of gear noise. There is a convergence of traditionally separate disciplines – gear design, structural dynamics, acoustics, and control – in service of solving the gear whine problem.

Future outlook: The coming years will likely see further integration and refinement of these methods. We anticipate **faster and more automated NVH prediction**, aided by machine learning surrogates and standardized data exchange between metrology and CAE. All-in-one optimization of gear systems for NVH, alongside strength and efficiency, will become routine as computational limits expand. On the research side, challenges like high-frequency “ultrasonic” gear noise, the influence of new materials (composites, novel alloys) on NVH, and active noise control approaches provide fertile ground for exploration.

From an industry perspective, multiphysics NVH simulation is transitioning from a specialist activity to a **must-have, built-in part of gearbox development**. Manufacturers of automotive transmissions, e-axles, and even industrial gearboxes (where noise regulations are tightening) are increasingly requiring that NVH be addressed via simulation **before prototypes are cut**. This proactive approach results in fewer surprises and less costly fixes – a clear economic benefit.

In summary, the state-of-the-art techniques and tools reviewed in this article empower engineers to **trace a path from the minutiae of gear tooth surface finish all the way to the subjective sound quality in a vehicle cabin**. By doing so, they can ensure that vital drivetrain components meet the ever more demanding NVH expectations of modern consumers – particularly in electric vehicles, where quietness and sound quality are defining attributes. The literature and examples cited illustrate that, although no simulation is perfect, the combination of improved physical models, richer data (from measurements), and greater computing capabilities has brought us closer than ever to a virtual “first-time-right” design for low-noise gears and gearboxes.

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