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NVH Analysis Within the Design Process

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> "If you want to find the secrets of the universe, think in terms of energy, frequency and vibration.
> — Nikola Tesla"

Introduction

At times, in the midst of troubleshooting an automotive transmission or axle gear whine problem during the launch phase of a new vehicle program, a powertrain NVH (noise, vibration and harshness) engineer might be inclined to agree with Mr. Tesla, that the solution to the issue at hand just might in fact be a secret of the universe. Many such exercises begin with "ear to gear" engineering implemented by an unknowing individual while driving a reportedly noisy vehicle. The timeless engineering process that goes something like: "I hear gear whine; something must be wrong with the gears. Perhaps bent teeth? Fix the gears." The gear and/or NVH engineering team's reaction is often a silver bullet approach: trying every countermeasure that has worked in the past, as fast as possible, one at a time. This behavior is not only commonplace, but for the most part, still an accepted practice throughout not only the automotive landscape, but all industries when dealing with passenger compartment gear whine issues.

For a while, at least in the automotive industry, it seemed as if management of passenger compartment gear whine had reached a certain level of containment; road, wind and internal combustion engine noise provided just enough masking, vehicle structural and acoustic sensitivities were being properly managed, and high quality gears were being manufactured, such that tonal noise from the transmission and axle were barely perceptible in most new vehicles, let alone annoying. Major OEMs were grinding gears specifically for controlling quality, and generally, most gear design engineers understood that high levels of gear transmission error equate to passenger compartment gear whine. Automotive companies were willing to invest in higher levels of sound packaging for vehicles, as well as engineering chassis that were less sensitive to gear mesh forces.

Perhaps it was the dual effects of the Great Recession and the Green Movement, but, in recent years passen-

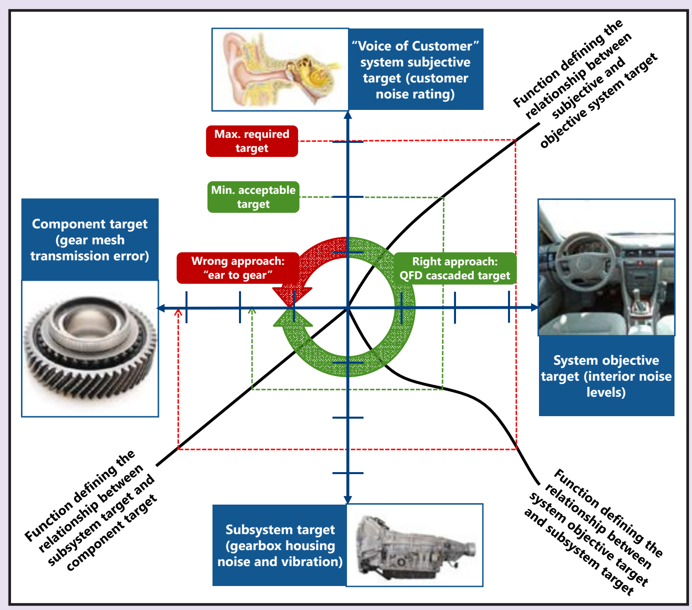
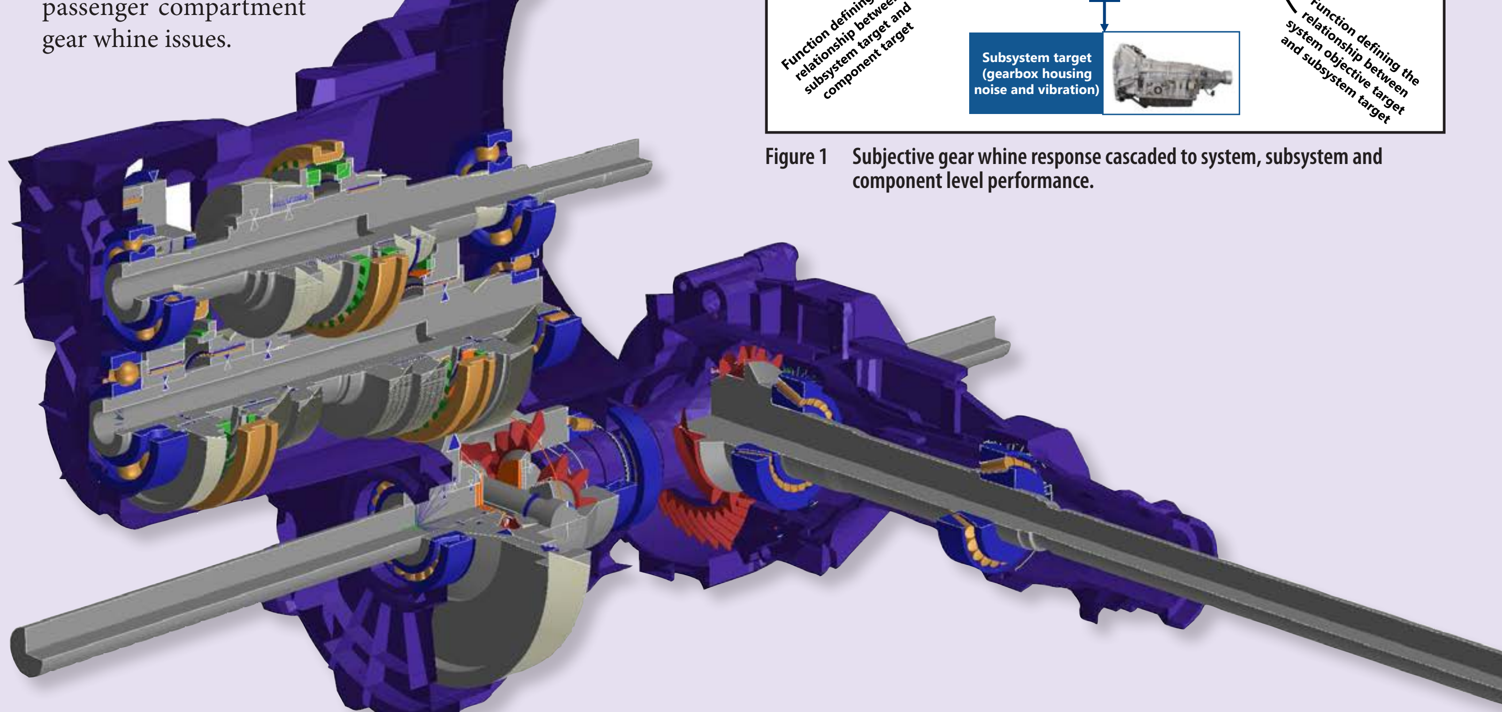


Figure 1 Subjective gear whine response cascaded to system, subsystem and component level performance.



ger compartment refinement of tonal noises has suffered from:

1. less investment in sound packaging,
2. less experienced powertrain and chassis NVH engineers following massive retirements of the skilled work force,
3. alternatives to internal combustion engines, including the increasing popularity of hybrid and electric vehicles, thereby reducing the effects of engine masking, and
4. a slight shift away from expensive gear grinding operations, compromising gear quality.

An additional important trend contributing towards increased passenger compartment gear whine includes the major automotive transmission OEMs producing 8+ speeds in automatic transmissions in order to help improve fuel economy, but struggling to properly manage the planetary mesh forces for optimal NVH. The practice is to select the planetary tooth numbers and spacing (phasing) such that the energy in the mesh is significantly reduced. However, the complexity of such planetary designs often produces unexpected energy in sidebands surrounding the main mesh frequency, and as well as the associated mesh harmonics.

Ideal Design Process for Managing Gear Whine

The customer is always right. This is a basic principle regarding customer products or services. As such, the "Voice of the Customer" should be factored into the design of all consumer products, including the noise performance of transmission and axles, along with other performance attributes such as durability, efficiency, cost, weight, etc. A quality function deployment (QFD) approach is useful for visualizing how gear micro-geometry, for instance, could be directly linked to subjective passenger compartment gear whine (Figure 1).

With a little imagination, an allowable variation in passenger compartment subjective ratings could translate into not only gear macro/micro-geometry design targets, but also allowable manufacturing variation for the gears. Practically speaking, the Voice of the Customer should be used to help the manufacturing team decide between rolling, shaving or grinding gears. In order to establish a firm link between subjective ratings and objective performance measurable by microphones, major automotive OEMs establish tonal noise targets for the passenger compartment based on studies performed and documented by Zwicker and Fastl (Ref. 1). These psychoacoustic theories outline how human hearing processes tonal noise in the presence of both broadband noise (tone-on-random masking) and other tones (tone-on-tone masking) (Ref. 2).

If using a source-path-receiver (SPR) model for gear whine, or any product noise for that matter, the customer derived tonal noise targets fit nicely into the "receiver" category, as shown in Figure 2. Clearly, managing the "path" is equally as important as managing the "source." Simplistically, for an automotive transmission, the "path" is represented by the transfer of forces from the gear mesh, through the shafts and bearings, ultimately causing the transmission housing to vibrate. Likewise, another "path" follows the forces from the vibrating transmission system through the various structure-borne and airborne paths of the vehicle, eventually arriving in the passenger compartment. This path from the transmission system to the passenger compartment is often quantified by performing a noise path analysis (NPA), or also commonly referred to as transfer path analysis (TPA); automotive OEMs establish targets for the path parameters, as part of managing the entire chain of passenger compartment gear whine (Ref. 3).

It should be noted that the QFD, SPR, and NPA/TPA quantifications of gear whine can be applied to any product in any industry. For example, wind turbine gearboxes and the resulting neighborhood noise (Ref. 4); agricultural transmissions and axles resulting in extraneous pass-by noise; helicopter gearboxes resulting in operator cabin noise, possibly affecting pilot fatigue. The product list demonstrating signs of gear whine is endless: household appliances, power tools, recreational vehicles, buses, mining trucks, construction equipment, material handling vehicles, etc. In fact, if you know a powertrain NVH engi-

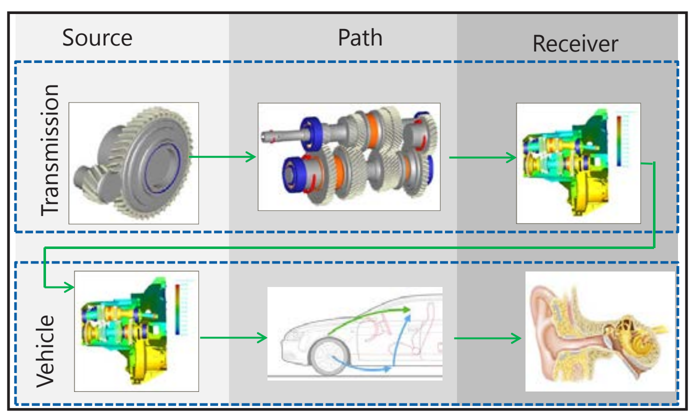


Figure 2 Source-Path-Receiver Models for Transmission and Vehicle Systems

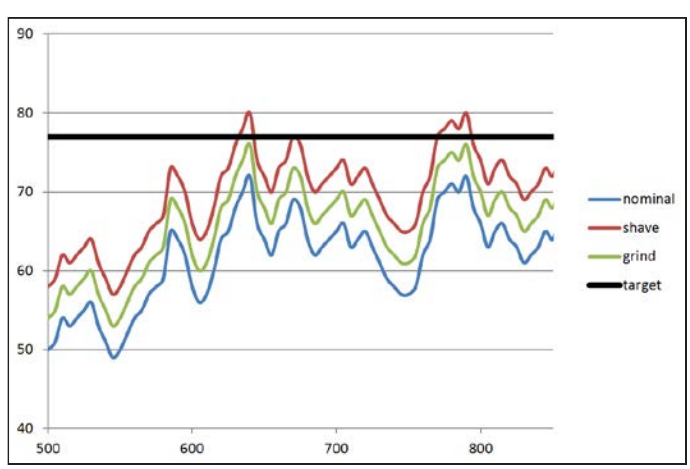


Figure 3 Radiated Gear Noise vs. Tonal Target

neer, you have most likely witnessed the endless subjective ratings of all things in their immediate environment, to the frustration of many spouses. So much to improve upon!

Two schools of practice exist regarding the gearbox design process. Despite the ever-growing reliance on using cutting edge CAE tools up-front in the design process, the experienced-based approach—driven by design rules, a decent spreadsheet for sizing gears, a reliable CAD package, and fundamental know-how about gear and bearings—maintains a strong following, especially in low-volume heavy industrial sectors. The reasons for this are clear: if it works, use it. And, outside of the automotive industry, gear whine issues perhaps are not at the top of every gear train development engineer's list; should an issue arise, it is dealt with appropriately. In recent years, however, I have noticed that on average the experienced gear designers are approaching the twilight of their careers, and despite the best efforts by institutions such as Ohio State University to fill the coffers, experienced-based design work is subsiding naturally due to this attrition. Coupled with the need for all manufactured gearboxes to be competitive globally in terms of cost, weight and performance, regardless of volume, the need to integrate more modern CAE tools is also rising rapidly.

Therefore, using advanced CAE tools focusing on gear and bearing analysis, an engineer with drivetrain design responsibilities is able to predict certain performance behaviors well ahead of any design-freeze dates, and preferably well before the tooling is ordered. In fact, the CAE tools are now advanced to the point where it's possible to simulate a virtual dynamometer, which is able to evaluate the NVH, durability and efficiency performance within the same software environment, for not only a nominal design, but also factoring in manufacturing variation.

Taken a step further, various manufacturing processes may also be evaluated within the context of mass-production. Figure 3 shows such a gear whine prediction exercise, factoring in gear micro-geometry variation due to both a shaving and grinding process, and comparing the results to a tonal noise target directly related to passenger compartment subjective ratings.

A quick review of the plot shows why gear whine issues may emerge during the critical launch phase. Note the nominal designs all reside below the defined tonal noise target. This is a normal expectation, since prototype gears are often watchfully ground or shaved with non-production tooling, with the intention of producing gears as close to the print design as possible.

But, if the effects of the manufacturing variation are factored in for the shaving process, it's clear that even with all dimensions well under control, a certain percentage of the production population will exceed the allowable tonal noise limits. Alternatively, the predicted noise performance of the population using the grinding tolerances will be under the target.

The purpose isn't to show that grinding is required; the purpose is to show a methodology factoring in relevant population performance when making critical design and manufacturing process decisions, as early as possible. If the program direction from the example is to use shaving, a re-design to improve transmission error is easier to implement before the design freeze and tool-ordering dates. This variation information is practically impossible to acquire using test or, within a certain range of uncertainly, using "experience" only. The advanced CAE tools improve the OEM's ability to make smarter choices for prototype builds and subsequent testing by pinpointing critical features and identifying worst-case production assemblies, in addition to predicting nominal performance, so the testing can better represent the full range of production possibilities.

Troubleshooting 101

Invariably, despite the best efforts of both the experience-based approach and the up-front-CAE approach, transmission and axle gear whine issues will often emerge. Complicating the engineering challenge is the trend towards development of traditional multispeed automatic transmissions, with complexity well beyond previous hardware generations, and of single- and two-speed transmissions for electric vehicles, with pitch-line velocities approaching or surpassing those usually associated with superchargers and other high-speed gearing applications. Understanding how the advanced CAE tools can best be used for addressing a current production gear whine issue will help both product and manufacturing engineering teams resolve the issue at hand by using a physics-based approach for developing effective countermeasures.

But first, when presented with an automotive transmission gear whine problem, for instance, the intelligent investigator will ask a series of questions, intended to help focus on the area of greatest concern for development of robust, representative CAE drivetrain models. The questions for an automotive application are provided here for consideration, and can easily be adapted for any gearbox in any industry.

Automotive Transmission/ Transaxle Gear Whine

Standard Troubleshooting Questions

1. What is the nature of the NVH problem? Is it tonal noise?
2. If yes, does it track with engine speed or wheel speed?
3. FWD, RWD-based?
4. If you completely disconnect the shift cable from the transmission/transaxle, does the noise diminish? Show data. Be careful not to run anyone over!
5. Is the tonal noise present in all gears or just some gears?
6. Drive, coast or cruise/float conditions?
7. Is it sensitive to throttle position (gear train load)?
8. Is this a current production vehicle, pre-production/prototype?
9. URGENCY
   a. How urgent?
   b. Holding up launch?
   c. Warranty costs?
10. All vehicles or some vehicles?
11. If this is a current production vehicle, was the gear whine quiet at launch, then it came on recently? Or, was it always present?
12. For the current gear whine issue, are the gears made to print? Show data.
13. Can you identify a "best of the best" (BOB) and "worst of the worst" (WOW) vehicle?
    a. Swap transmissions. Does the whine follow the transmission or the vehicle?
    b. If it follows the transmission, tear down the noisy transmission and re-build it. Is the noise still present at the same levels? If so, swap out the suspect gears. Is the noise still present?
14. Tell me about the transmission/transaxle configuration
    a. Manual
    b. Automatic
    c. Dual-clutch transmission
    d. Are you sure the noise is not: Power-take off
    e. Are you sure the noise is not: Transfer case
    f. Are you sure the noise is not: Axle
    g. Are you sure the noise is not: engine accessory related
15. Does the noise get worse/better/same with temperature?
16. Is the same transmission/transaxle used in another application? Such as a different model, etc. Is the WOW or noisy transmission also noisy in this other application?
17. For FWD, if the noise emerged recently and not always, *something changed*. Was it the half-shafts? Wheel hubs? Mounts? Sound package? Shift cable? Change suppliers/ materials on *any* of the above? Are you sure? Sometimes a part may be assigned the same number, and look the same, but tolerancing/materials could be different.
18. Any End-of-line control in transmission/transaxle plant? Gear quality SPC charts? Gear inspections?
19. What is the gear manufacturing process? Did anything change?
20. IMPORTANT: what is the noise path from the gear mesh to the passenger compartment? Are you sure? Show data.
    a. NPA techniques: inverse matrix, dynamic stiffness
    b. Poor man's NPA: various disconnects/wraps
21. Are sidebands present? Spacing?
22. Does the noise occur at a single speed/frequency ("peaky"), or is it present across all speeds/frequencies, or both?

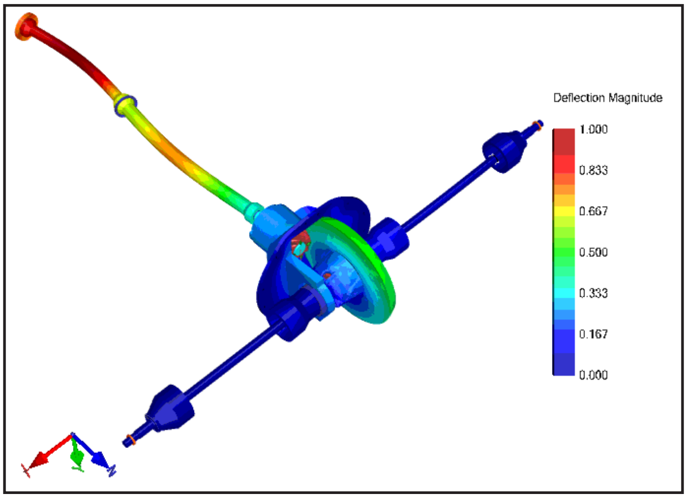


Figure 4 Mode Shape Analysis in *RomaxDESIGNER*

23. If you perform a neutral engine run-up, is the noise present?

The responses to the questions above will dictate the type of CAE model the investigator needs to create, and, actually establish if the tonal noise is even related to the transmission in question. Often, tonal noise from other sources is confused with transmission noise. If the NVH issue is indeed gear whine, and is present in all transmissions, and not just a few, then the fundamental issue could very well be related to the basic gear design. If limited to only a few transmissions, then the issue could be a special cause in manufacturing, such as an emerging tooling or assembly issue, excessive heat treatment distortion, material quality issues, etc. The CAE approach would be quite different either way.

Likewise, the issue could be related to a changing vehicle path, such as a transmission mount re-design for durability issues, resulting in less isolation for housing vibration; many gear manufacturing engineers have spent many long hours "fixing" gears due to vehicle issues and the application of "ear to gear" engineering as previously explained. The questions above help the troubleshooting team focus on the physics of the problem, not the politics.

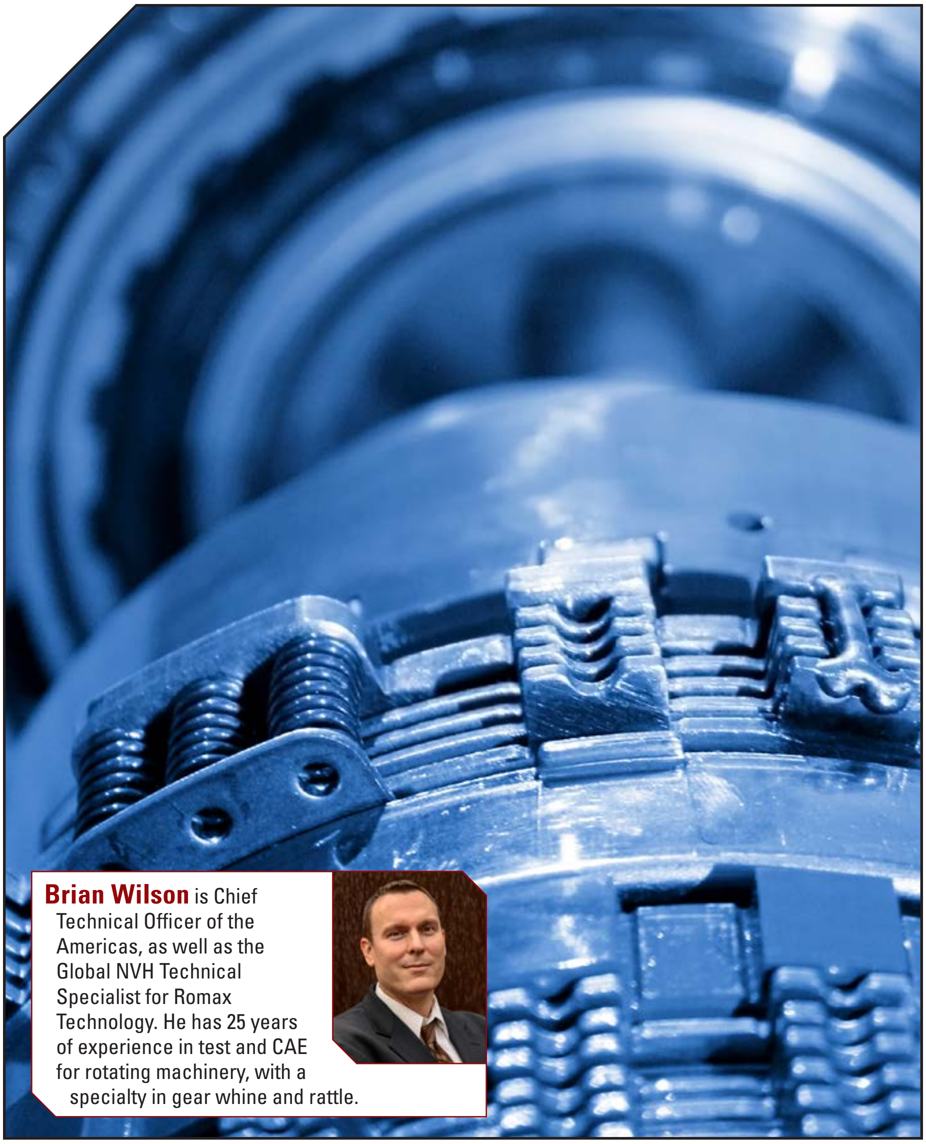
A few basic guidelines for creating a robust and representative CAE model of the transmission for gear whine analysis:

1. **Model what is tested; never test what is modelled:** A drivetrain CAE tool capable of analyzing the entire transmission *system*, including gears, bearings, and housings should be used, especially for planetary-based or multi-mesh drivetrains (Ref. 5). This includes full tooth topologies from multiple teeth from each gear, in order to perform an accurate non-linear gear contact analysis. All flexible elements should be properly modelled with dynamics-quality meshes, including the housing, carriers, ring gears, and shafts for planetary-based transmissions. Carrier pinion spacing errors, gear pitch errors, component eccentricities and concentricities related to assembly variation, and accurate bearing geometries are all critical pieces of information required to build a representative drivetrain dynamics model with proper gear and bearing contact mechanics.
2. **Boundary Conditions:** The drivetrain CAE model should include representations of the boundary conditions that match the actual hardware (Refs. 6, 7). If test-based evaluations are to be performed in-vehicle, on a dynamometer, or in some cases, using the end-of-line test system, then the CAE model needs to perfectly reflect the upstream and downstream hardware in order to properly capture the drivetrain dynamics. The extent of the required boundary conditions will vary, depending on the system under investigation. See Figure 4 for an example.
3. **Customer-Derived Metric:** The CAE predictions should tie in directly with customer-derived metrics based on an NPA study, such as radiated noise, mount vibration, or output shaft torsional vibration, used in conjunction with derived tonal noise targets based on passenger compartment response. Knowing the magnitude of the required reduction in noise or vibration is important to the development of effective countermeasures.

If used effectively in a transmission product development process, the same up-front CAE tool used for establishing the fundamental design can also be used for troubleshooting unexpected hardware issues. This assumes the investigator knows the correct questions to ask, and like Tesla suggested, is able to properly interpret the responses in terms of energy, frequency and vibration.

References

1. Zwicker, E. and H. Fastl, *Psychoacoustics: Facts and Models*, Springer-Verlag, 1990.
2. Blommer, M. and M. Clapper, "Masking Perception Analysis Software (MPAS) for Tonal Noise Setting in Powertrain NVH," SAE 2003-01-1500.
3. Williams, J. S., G.C. Steyer and J. Ditman, "Transmission Tonal Noise: Experimental Analysis of the NVH Characteristics Which Influence Vehicle Sound Quality," *Proceedings of the IMAC XIV*, Feb. 1996.
4. Abe, T., Y. Cheng, K. Nowaczyk and B.K. Wilson, "Practical Methods for Managing the Gear Whine Phenomena," *Proceedings of ASME 2007 10th International Power Transmission and Gearing Conference*, Las Vegas, Nevada, USA.
5. Abe, T., Y. Cheng, M. Felice, J. Pears, M. Platten, A. Smith and B.K. Wilson, "Predicting Variation in the NVH Characteristics of an Automatic Transmission using a Detailed Parametric Modeling Approach," SAE 2007-01-2234.
6. Jamaluddin, R., E. Stilwell, and B.K. Wilson, "Boundary Conditions Affecting Gear Whine of a Gearbox Housing Acting as a Structural Member," SAE Paper 2009-01-2064.
7. Wilson, B., G. Peterson, A. Kulkarni and A. Kanase, "CAE Techniques for System Analysis of Hypoid Gearset Vibration," SAE Technical Paper 2011-01-1502.



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