The Importance of Integrated Software Solutions in Troubleshooting Gear Whine

Paul Langlois

NVH — noise, vibration and harshness — is a key issue in the design and development of modern transmission and driveline systems. A combination of regulations and consumer expectations drive a demand for reduced noise in all drivetrain components. Further demand is driven by the growing trend towards EV and HEVs where noise from internal combustion engines is intermittent or no longer present and the contribution of transmission noise to overall vehicle noise becomes dominant, making it more difficult to achieve customer satisfaction. So how do these problems occur? How can they be controlled? And what role can integrated software play in the troubleshooting process in order to obtain efficient and effective solutions?

Gear Whine Analysis Requires a System Level Approach

Gear whine is an NVH phenomenon most commonly sourced from transmission error (TE) at engaged gear meshes. Theoretically, an infinitely stiff gear set with perfect involute form and no misalignment would transfer angular velocity exactly in accordance with the designed ratio. However, in reality, no gear is perfect and, for example, tooth bending and misalignments caused by deflections of the system contribute to real gears not performing to this ideal. TE is the difference between the angular position that the output shaft of a drive would occupy if the drive were perfect and the actual position of the output (Ref. 1). Other potential, but less common, sources of gear whine whose fundamental frequency is also at once-per-tooth include axial shuttling forces — where the axial location of the resultant force varies through the mesh cycle, resulting in a varying moment on the gears; and friction forces from the relative sliding at the gear mesh (Ref. 2).

Transmission error can be considered a periodic relative displacement at the gear mesh in the line of action caused by less-than-ideal meshing conditions. The TE can dynamically excite the transmission through a path from the gear mesh, through the shafts and bearings and into the transmission housing. Gear whine is the name given to the resulting tonal noise radiated from the housing or transmitted from the housing to be radiated elsewhere. Gear whine should therefore not just be considered a *gear* problem; it is a *system* problem with the gears as the exciters of the system.

As a typical source-path-responder dynamic phenomenon, gear whine issues can be difficult to troubleshoot. It is often considered that the solution to gear whine can always be found by optimizing the gear microgeometry to minimize the excitation. Although controlling transmission error will reduce gear whine, and can often be the best approach to doing so, a gear mesh with minimal transmission error may still be a cause of gear whine issues if the rest of the system is highly sensitive to excitations at the gear mesh. Each stage of the process should, and may have to, be considered in the search for a potential solution. Further, by increasing the solution space to include the optimization of gear macro geometry for gear whine and via consideration of the stiffness and mass of the supporting structure and housing, greater improvements can be achieved.

As gear whine is a system-level NVH issue, for simulation of these contributions and virtual testing of potential solutions a full system level modelling and analysis approach is required.

A Full Testing and Simulation Methodology

To solve NVH problems, a combination of experience and the right tools are required to find solutions with minimal cost and timescale. An efficient NVH troubleshooting methodology requires a process where accurate measurements and detailed CAE simulations can be performed side by side and data processed and communicated error-free between testing and analysis teams using integrated software solutions. Integrated software solutions for gear whine NVH are those that can perform measured data capture and analysis and all relevant system-level simulations in one integrated environment with seamless data transfer — such as those, for example, offered by SMT (Fig. 1). The purpose of this article is to discuss the role these integrated software solutions play in this process, with the understanding that it is beyond the scope of this article to describe the complete problem-solving methodology.

The first recommended step would be to check manufacturing and assembly

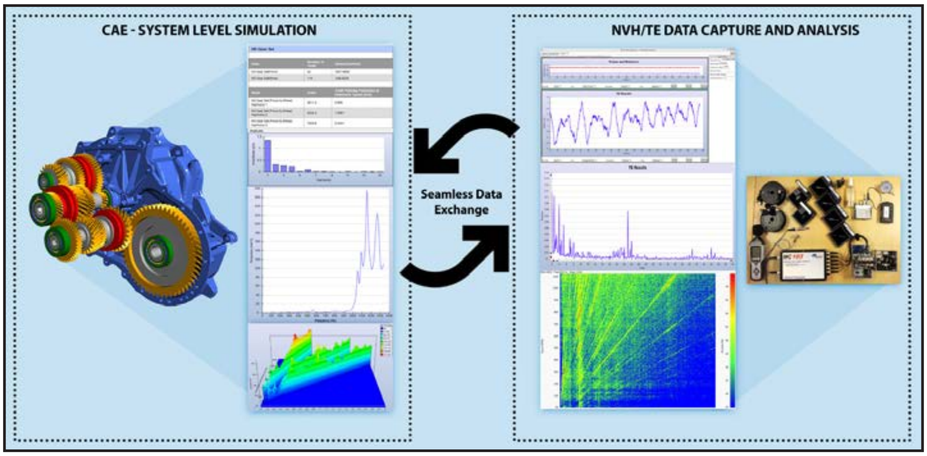


Figure 1 An integrated software solution for gear whine combining measured data capture and analysis with system-level simulations in a single environment with seamless data transfer.

quality. If quality is poor, e.g. — outside the required tolerances — then TE can be high and these issues need to be resolved before steps in addressing the design are taken. Software can play an important role even at this stage, where cylindrical gear manufacturing simulation achieved by SMT *MASTA* software (Ref. 3) can help improve manufacturing quality and resulting TE. In addition, the same software can be used to carry out parametric studies to identify and adjust manufacturing tolerances to reduce assembly-to-assembly-related TE variation.

Software plays two main vital roles in the further troubleshooting process: 1) within the test environment, where high-fidelity data logging is required to capture test results and where results need to be processed using data analysis tools to effectively analyze the measurements and identify the features of interest and the main contributors from the system to those features; and 2) within the simulation environment where state-of-the-art, system-level simulation tools are required to perform a number of simulations of aspects of the system — details of which will be described later in this article. Correlation between simulation and test can be made, and the simulation model then used as a virtual environment for assessing the effect of potential solutions on all requirements and targets. Changing component parameters in a virtual environment is a quick, low-cost approach that minimizes the need for expensive and time-consuming hardware trial-and-error loops.

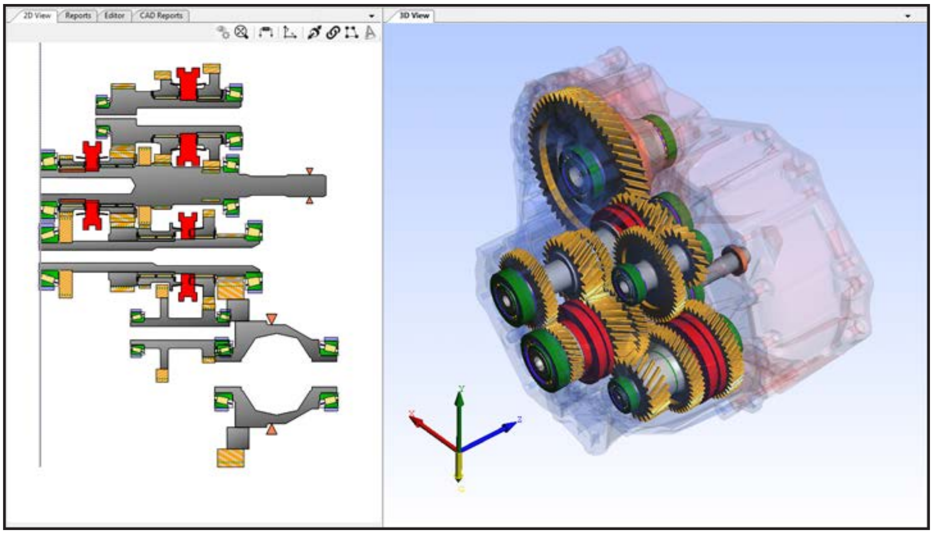


Figure 2 A system-level transmission simulation model.

Integrated software solutions allow all these tasks to be performed in a single software environment. At the testing stage, data from proprietary, portable hardware for both noise, vibration and transmission error measurement can be captured, post-processed, and analyzed, using in this case SMT's TE and NVH data capture and analysis software — *MEASA*. Further, the measured data analysis tools can be linked to SMT's

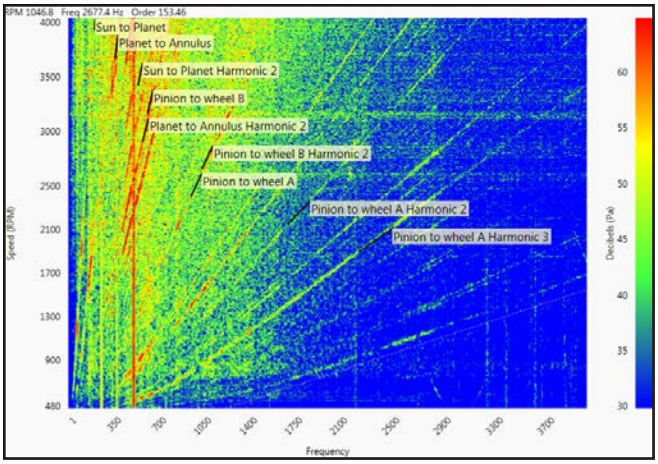


Figure 3 **Measured noise displayed as a waterfall plot with excitation orders automatically labelled via data from a system simulation model.**

mentioned transmission design and analysis software, *MASTA* (Ref. 3), where orders from potential excitations within a corresponding analysis model of the system can be passed to easily identify contributions from transmission components while processing measured data.

Within a simulation environment, *MASTA* allows for analysis of many aspects of the problem; a single model of the system is easily built within the software (Fig. 2). This single set of parameterized inputs can then be used to perform a number of analyses for a number of failure modes and phenomena of interest, using automatically constructed analysis models of differing levels of fidelity. Analyses of interest for gear whine include: static analyses of the full system under a number of operating loads to calculate deflections of the system and their effect on durability of components; quasi-static analyses of the loaded gear mesh contact conditions to calculate contact stresses, root stresses, transmission error and shuttling forces; modal analyses of the full system to calculate system-natural frequencies, mode shapes and modal energy content; and gear whine analyses of the full system to calculate the dynamic response of the system to excitation by transmission errors.

Test Data Capture and Data Analysis Software

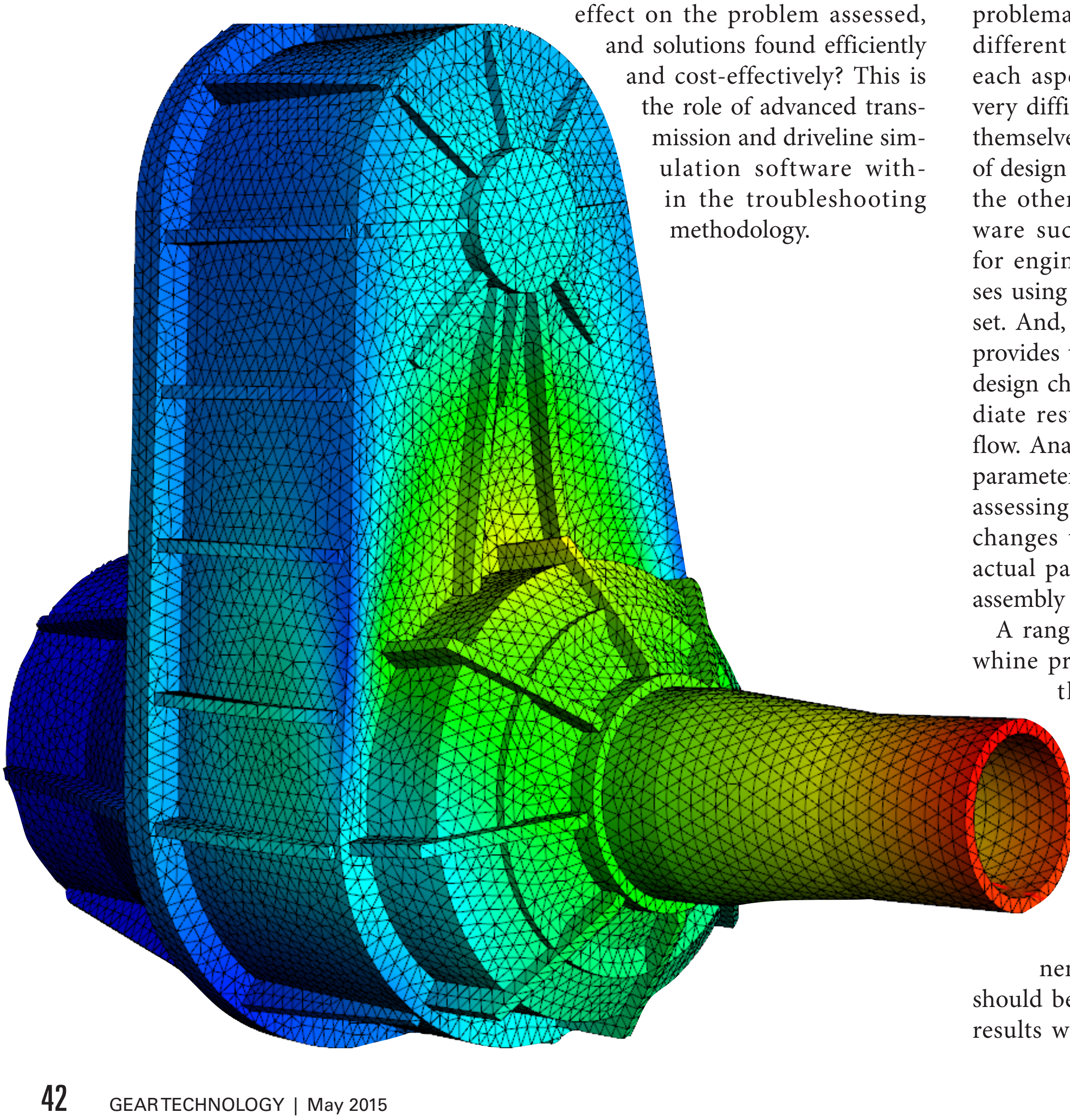
For gear whine issues typical measurements considered include noise measurements via microphones, casing vibration measurements via accelerometers, and transmission error measurements via angular encoders.

Measurements of gear whine should include tests performed in-vehicle that capture the full operating range through, for example, vehicle accelerations at different throttle levels and vehicle coastdown. Further dyno rig tests should be performed to isolate and understand transmission and driveline noise sources. Care must be taken in correlating any rig test results with those of vehicle tests and the original subjective noise problem. Different boundary conditions on the rig, as compared to in-vehicle, can significantly change the dynamics of the system and subsequent frequency content of problem areas (Ref. 4).

Accurate data acquisition requires calibrated microphones and accelerometers and high-fidelity data logging. Further, an accurate speed signal is required for analysis of component orders. Measurement data can be captured and analyzed using *MEASA* data capture and analysis software. Data analysis tools allow the user to process the data in a number of ways. By linking to a model of the transmission system under consideration, potential excitation orders and the components and harmonics to which they correspond may be imported into the data analysis tools to allow easy identification of the main contributions to specific orders and to the total noise/vibration content. Critical plots given include waterfall plots and order cuts giving quantitative results for the noise due to specific sources and their prominence with respect to total noise (Fig. 3).

Although less common than noise and vibration measurements, the source of gear whine — loaded transmission error — can also be measured using angular encoders. For a transmission or driveline system on a test rig, encoders may be placed on the input and output shafts in order to measure the whole gearbox, or may be placed straddling a sub-system to measure just that sub-system. As with noise and vibration test results, TE test results may be captured and analyzed using *MEASA*. Fourier analysis can be performed to identify the contributions from different stages and angular TE values can be converted to linear via the base radius values for the gears. A link to a model of the system allows import of gear mesh orders and their harmonics for easy identification within the data analysis tool.

Using these measurement and data analysis techniques, the nature of the noise issue can be quantified and the contributions from the potential excitations in the transmission identified. But how can design changes be made, their effect on the problem assessed, and solutions found efficiently and cost-effectively? This is the role of advanced transmission and driveline simulation software within the troubleshooting methodology.



Full System Simulation

Once a gear whine issue has been identified and the contributions clarified via measurement and data analysis techniques, simulation software plays a vital role in efficiently assessing potential solutions. As gear whine is a system-level issue, where solutions may be considered from gear macro geometry design, gear microgeometry design, system stiffness and mass properties and the transmissibility of TE to the casing, state of the art system-level software is required to be able to perform various analyses of interest. Design changes need to be assessed effectively — not just for their effect on the noise problem at hand — but also for other considerations of importance in the design process so as, for example, not to compromise durability.

Such durability, loaded tooth contact and dynamic response analyses may be performed using standalone commercial FE packages. However, this approach is problematic as it requires models with different levels of fidelity to calculate each aspect. What's more, models are very difficult to set up and do not lend themselves well to analyzing the effects of design changes easily and quickly. On the other hand, integrated CAE software such as *MASTA* provides tools for engineers to perform these analyses using a single model and parameter set. And, model generation is rapid and provides the flexibility to make complex design changes on the fly, seeing immediate results within a seamless workflow. Analyses are fast enough to enable parameter space DOE studies, including assessing the robustness of any design changes to the expected variability in actual parts due to manufacturing and assembly tolerances.

A range of analyses relevant for gear whine problems can be performed on the system-level model. To begin, a number of static analyses are usually performed covering the operating range to calculate deflections of the system, including misalignments at gear meshes, and durability results for components. Baseline durability results should be obtained and compared with results when design changes are made

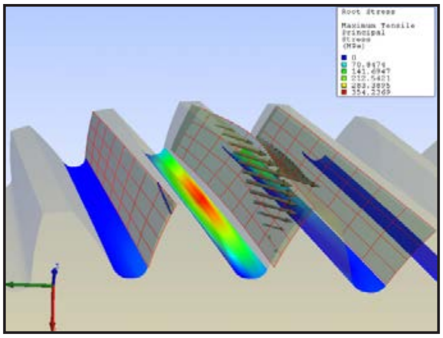


Figure 4 Hybrid FE and Hertzian-based loaded tooth contact analysis.

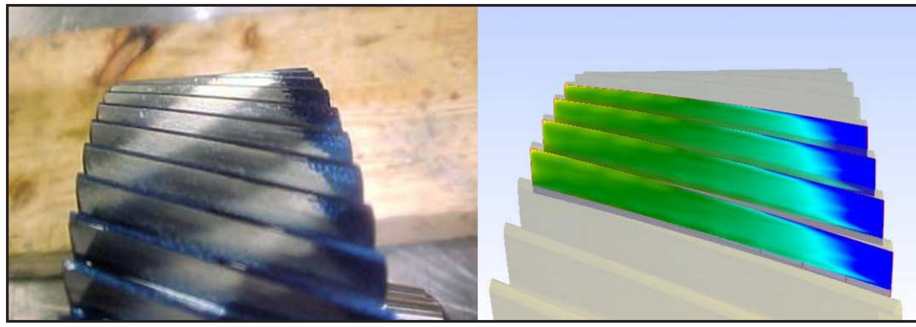


Figure 5 Measured and simulated loaded contact patterns.

to check that no compromise in durability is introduced. The system deflection model consists of an FE-based model where shafts are considered as Timoshenko beam elements; bearings are represented via a bespoke non-linear contact formalism, taking into account the full geometry details; clearances, preloads, etc., gear meshes are represented as bespoke non-linear contact models; and housings and complex asymmetric shafts are included via stiffness and mass matrices obtained via dynamic reduction from a full FE model of the geometry. Durability results for bearings, gears, shafts and other coupling components are obtained by passing deflections and loads from the analysis results to implementations of the relevant international standards (Refs. 5–7).

Although it should be noted that the solution to gear whine does not always lie in optimizing gear microgeometry, this is often the first area of investigation due to its relative ease. Further, if late in the development process, this is often the easiest option to implement due to the minimal change to manufacturing processes and tooling required. Calculation of TE can be performed using a loaded tooth contact analysis (LTCA). Torque, misalignment, gear macro and microgeometry are used as inputs. It is very important to use an accurate LTCA in order to get an accurate calculation of TE. A hybrid FE and Hertzian, contact-based formalism are used to accurately capture the stiffness at each contact location while providing a fast calculation suitable for assessing microgeometry parameter changes and robustness to tolerances (Fig. 4). Such a calculation is comparable in accuracy to a full FE contact analysis while being many orders of magnitude faster. An FE model of the gear macro geometry is built automatically in the software and used to obtain the overall bending and base rotation stiffness of the gear teeth, with consideration made for coupling between teeth. This bending stiffness is combined with a Hertzian line contact formalism to calculate the overall stiffness of any potential contact points. Potential contact lines are split into strips and force balance and compatibility conditions are formulated and solved (Ref. 8) to calculate the load distribution across the mesh and the transmission error for the input torque. This LTCA can be used to optimize gear microgeometry and macro geometry for minimal transmission error. Consideration must be given to the entire operating range of loads and the robustness of the proposed design to variation in load and misalignments, as well as variation in gear microgeometry within the manufacturable tolerance range.

It is often assumed in the analysis workflow described above that the deflections of the system affect the tooth contact — but the tooth contact conditions do not affect the deflections of the system. Hence, as above, a calculation of misalignments is first performed using a static system-level model, and these misalignments, assumed constant throughout the mesh cycle, are used as inputs into the tooth contact calculation. This assumption is often — but not always — valid. In a number of important cases, such as the tooth contact conditions of a planet gear, the interaction between the two meshes of the planet means that the system deflection and tooth contact conditions need to be solved in a coupled calculation. In such a calculation the assumption of a fixed misalignment throughout the mesh cycle is removed and the variation in misalignment is calculated. Further, for planetary systems where contact conditions may vary, as the planet carrier rotates, such a coupled calculation is required. The software solutions discussed here also provide such a calculation.

Tooth contact analysis results can often provide good validation that the analysis model is set up and performing correctly. A contact patch test is a relatively easy and common test to perform and contact patch test results can be compared directly against analysis results (Fig. 5). If correlation is good, this gives confidence in the analysis model, implying that calculated misalignments, microgeometry inputs, and calculated load distribution under the tested loads are accurate. Further, if TE measurements have been performed, measured and calculated, TE can be directly compared.

Analysis of the dynamics of the system can be performed via modal and harmonic response analyses. For a modal analysis of the system at a given input load, a linearized model of the non-linear static analysis model at that load is automatically built. The natural frequencies and corresponding mode shapes can therefore be calculated for different operating loads. Campbell diagrams can be used to identify potential excitations of the system where, for example, gear mesh frequencies or their harmonics cross the natural frequencies of the system. Further, the energy content of the mode shapes can be visualized and investigated to identify the main contributing components to those potential resonances (Fig. 6). A target would be to minimize the number of natural frequencies within the operating range while also separating any way in which do lie within the range from each other.

The method of calculation of the system response to the transmission error introduced by Steyer et al (Ref.9) can be used to calculate the casing acceleration at virtual accelerometer locations. As the excitation is periodic and the stiffness around the loaded condition can be considered linear, the calculation can be performed very quickly in the frequency domain. Static transmission error is the assumed excitation input of the system and the first step is to calculate the dynamic force at the gear meshes, which leads to a relative displacement at the mesh given by this transmission error. This force is known as the dynamic mesh force that is calculated from the dynamic compliances at each side of the gear meshes. The dynamic mesh force is then applied as an excitation to the system model to calculate the response at any point on the system to this excitation. Waterfall charts can be plotted of dynamic response for any point on the model (Fig. 7) and compared with accelerometer and/or microphone data obtained via noise and vibration tests.

Once a virtual model is correlated with test data, contributing modes to problem frequencies can be identified via the waterfall charts and natural frequencies. Then, the contributing components to those modes can be identified with mode shapes and energy contributions. With the results obtained, the design of these components can be adjusted to improve the dynamic response of the analysis model. Once the desired results are obtained, the design changes can be implemented on a prototype and tested again to confirm the expected improvements.

Benefits of an Integrated Software Approach to Troubleshooting Gear Whine

- Reduced product development time by targeting solutions in a virtual testing environment.
- Reduced product development cost by minimizing component testing.
- Allows production variation to be investigated and minimized prior to product launch.

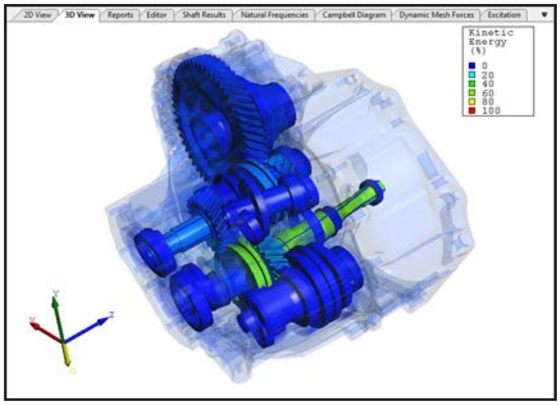


Figure 6 Mode shape and kinetic energy content of system mode at 701 Hz.

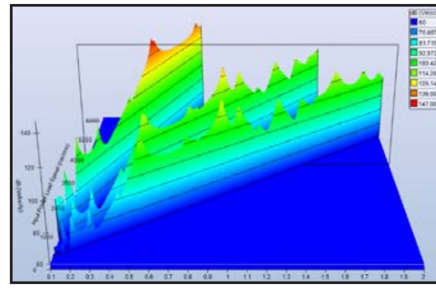


Figure 7 Calculated casing response to excitation by transmission error.

Summary

The development cycle of transmission systems is a complex and costly process. With increased demands for lower-noise transmissions and drivelines driven by markets such as EV and HEVs, more pressure is being placed on designers to design for low noise and for analysts to solve known gear whine issues quickly and efficiently. Quick solutions with minimal cost can be found with a combination of solid methodology, experience and the right software tools. Software plays a vital role within this process. Assessing, controlling and fine-tuning designs for gear whine within an integrated CAE environment, such as that offered by SMT, where test data capture and data analysis, together with advanced simulation methods, are seamlessly integrated, provides engineers with the flexibility and freedom to achieve new levels of quality otherwise too costly and time-consuming to achieve through physical prototyping alone.

References

1. Smith, J.D. *Gear Noise and Vibration*, Second Edition, Marcel Dekker, Inc. 2003.
2. D. R. Houser, D.R. et al. "Determining the Source of Gear Whine Noise," *Gear Solutions*, February 2004.
3. *www.smartmt.com/masta.*
4. Meinhardt, G. et al. "Correlation of Axle End-of-Line (EOL) NVH Performance and Laboratory Dynamometer Performance," *SAE 2005 Noise and Vibration Conference,* 005-01-2306.
5. BS ISO 6336-2: 2006(E). Calculation of Load Capacity of Spur and Helical Gears — Part 2: Calculation of Surface Durability (Pitting), 2006.
6. BS ISO 6336-3: 2006(E).Calculation of Load Capacity of Spur and Helical Gears — Part 3: Calculation of Tooth Bending Strength, 2006.
7. ISO/TS 16281: 2008(E). Rolling Bearings: Methods for Calculating the Modified Reference Rating Life for Universally Loaded Bearings, 2008.
8. Conry, T.F. and A. Seireg. "A Mathematical Programming Method for Design of Elastic Bodies in Contact," *J.A.M.* ASME, 2, 1971
9. Chung, C. and G. Steyer et al. "Gear Noise Reduction Through Transmission Error Control and Gear Blank Dynamic Tuning," *SAE Noise and Vibration Conference* 1999-01-1766.

Dr. Paul Langlois is CAE products development department manager at Smart Manufacturing Technology Ltd. (SMT). Having worked for SMT for 10 years, he has extensive knowledge of transmission analysis methods and their software implementation. He manages the development of SMT's software products and was a main contributor to many aspects of the technical software development, such as MASTA's gear-loaded tooth contact analysis and NVH functionality.