Eliminating Gear Whine

Advanced simulation techniques from Romax Technology eliminate gear whine problems in automatic transmissions.

By Dr. Michael F. Platten and Melanie Fitton-Hayward
THE INTRUSIVE NOISE KNOWN AS GEAR WHINE IS CAUSED BY VIBRATIONS GENERATED BY GEARS AS THEY MESH AS A RESULT OF IMPERFECTIONS CAUSED BY DESIGN, LOADING, TEMPERATURE EFFECTS, AND MANUFACTURING VARIATIONS. REDUCING GEAR WHINE NOISE TO AN ACCEPTABLE LEVEL IS A BIG CHALLENGE, ESPECIALLY FOR COMPLEX GEARBOXES LIKE THE MODERN PLANETARY AUTOMATIC TRANSMISSION. ADVANCED DESIGN, SIMULATION, AND ANALYSIS TOOLS LIKE ROMAXDESIGNER GIVE ENGINEERS THE ABILITY TO QUICKLY AND ACCURATELY IDENTIFY PROBLEMS, FIND THE ROOT CAUSE, AND PROPOSE REALISTIC SOLUTIONS WITHIN THE ALLOWABLE DESIGN CONSTRAINTS. WITH SUCH A TOOL, EXISTING DESIGNS CAN BE OPTIMIZED TO REMOVE NOISE PROBLEMS, AND NEW DESIGNS CAN BE CREATED THAT ARE KNOWN TO BE PROBLEM-FREE EVEN BEFORE ANY METAL IS CUT. HERE WE DEVELOP A PROCESS FOR OPTIMIZING AN EXISTING DESIGN TO REDUCE A NOISE PROBLEM AND SHOW HOW IT WORKS WITH A REAL-WORLD EXAMPLE.

Gear whine does not have to be loud to be a problem. It is by nature a tonal noise, which is annoying to drivers and passengers because it cuts through other noises in the vehicle interior. Perfect gears in a perfect operating environment produce no noise, but unfortunately we do not live in a perfect world. The real world is one of manufacturing and assembly tolerances, and components that deflect under the loads we put through them. The difference between the smooth transfer of motion by perfect gears and what you actually get in practice is called “transmission error,” or “TE.” This is the true source of gear whine noise. TE causes a vibration at the gear mesh which is transmitted through the internal gearbox components to the housing, where it is radiated directly as noise or transferred through the chassis in the form of vibrations to be radiated as noise elsewhere. Although not the sole method of controlling gear whine, reduction of the noise at the source by reducing TE is clearly a good idea.

The usual way of adjusting TE is through making changes to the tooth surface on a microscopic level. These “micro-geometry” modifications can be tailored to reduce TE, but to know what changes to make you need to understand how the gear teeth are behaving at a microscopic level. You also need to consider that any micro-geometry changes you make will also impact the durability and efficiency performance of the gearbox. It is no good having a quiet gearbox that breaks after 50,000 km.

A quick glance at fig. 1 will tell

Fig. 1: RomaxDesigner model of a six-speed automatic transaxle gearbox.
you that a modern automatic transmission is a complex beast, with many gears meshing simultaneously. These complexities make it difficult to predict the gear meshing behavior and to identify the optimal micro-geometry modifications necessary. The only way this can be achieved is by considering the gears within the context of the complete transmission. The effects of and interactions between all these gears mean that a system-level simulation such as that provided by RomaxDesigner from Romax Technology (a quick and accurate virtual product development tool with the capability to simulate, analyze and optimize the NVH, durability and efficiency performance of the most intricate designs) is a necessary tool in the process of making these gearboxes quiet.

**SIMULATION CHALLENGES**

Optimizing the design of multi-mesh planetary gearboxes presents a number of problems when compared to simpler manual transmission designs, which means that specific methods have had to be developed by Romax Technology to deal with automatic gearboxes.

**COMPLEXITY OF DESIGN**

A planetary automatic gearbox is complex with many components. To simulate it we need to represent that complexity but only to a level of detail that is necessary to give us the results we need—we do not want a cumbersome model that takes a lot of computer time to run, but we do need to include detail where it is important. For example we need a very detailed description of the gear geometry and a detailed model of gear tooth contact, but we only need to consider the simulation of brakes and clutches on a concept level. We also need to include the effect of the gearbox boundary conditions whether in the vehicle or on the test bench so that our model represents what we are actually testing.

**LOAD SHARING AND MISALIGNMENT**

Automatic transmissions achieve their high power density by splitting the transfer of torque through several planet gears simultaneously. System deflections due to internal loads, manufacturing errors and external radial loads (such as gravity and those from the transfer gear shown in fig. 1) destroy the symmetry of the planetary sys-
tem and result in unequal sharing of that torque between the planets. To make matters worse, this inequality varies as the carrier rotates relative to the sun and ring due to changes in the stiffness of the carrier, the effects of gravity and slight variations in planet pin position within the allowable manufacturing and assembly tolerances. The knock-on effect of this is that different torques in each gear mesh means different misalignments in each gear mesh and these also vary as the carrier rotates. A final complication is interactions between different gear meshes. In a planetary gear arrangement a planet gear is connected to at least two other gears. The misalignment at one gear mesh has an influence on the misalignment at other gear meshes because they are all connected by the same gear.

What this means practically is that the detailed analysis of these gear meshes which is required to correctly predict TE must simulate the effect of all gear meshes simultaneously (the case study on pg. 48 has 9 meshes). In addition the simulation must include the effects of the variation in torque and misalignment as the components rotate.

In RomaxDesigner this is achieved by performing an iterative static analysis of the entire gearbox at several different carrier rotation positions to build up a complete profile of the gear contact behavior considering all of the above complications. This is a relatively quick process due to the optimized algorithms used, giving an answer in a matter of seconds.

**Fig. 3:** Comparison between measured baseline housing vibration, simulated baseline housing vibration, and simulated optimized housing vibration.
**GEAR MESH PHASING**

When we look at gear whine caused by a simple gear pair, we can say that the resulting gear whine noise is directly proportional to the TE. This means that if we discover that we need to reduce the noise by 50 percent then we know that we have to reduce the TE by 50 percent. As with everything else, the planetary gearbox does not behave quite so nicely.

In the automatic transmission we have many meshes active at once, each producing their own TE all at the same time and all at the same frequency. However the relative phases of these TE signals are not always the same. The combined noise effect of all the TE signals together depends on the phasing. In some cases the signals add together and reinforce the resulting vibrations (and hence the sound heard by the driver); in others the signals cancel each other out and the vibration in a particular direction is reduced. These phase differences are generated at two levels: the majority of this phasing is determined by the number of teeth on the gears, the number and positioning of the planet gears and whether the gearbox as a whole is more sensitive to lateral or torsional dynamic forces. Small changes to the phasing are also caused by the micro-geometry design of the teeth. Paying attention to this phasing early in the design process is critical to a good gearbox design.

What this implies is that we cannot simply use TE as a measure of how good our noise performance will be for an automatic transmission, as there is no simple relationship between individual mesh TEs and the resulting noise in the vehicle. Instead we must use the vibration of the transmission housing as a measure of success or failure and that means we need a dynamic model of our gearbox.

**DYNAMIC RESPONSE**

Predicting vibration response behavior of a gearbox requires two things: knowledge of the excitation—in our case, the TE, which we know our methods can accurately predict—and also a dynamic model of the complete transmission system. We can apply the predicted TE at each mesh (including the phasing) in the dynamic model and predict the response at any location on the housing. These can be compared directly with vibration measurements on the real gearbox. RomaxDesigner includes the capability to automatically generate a dynamic model and calculate the response.

So there are many difficulties associated with the simulation of gear whine in planetary automatic gearboxes but we have been able to implement methods to cope with these within the RomaxDesigner virtual product development environment. Next we will see how these methods can be put to use in a gear whine troubleshooting process.

---

**LUREN**

“A cost-effective high-quality gear grinding machine”

**LFG-8040**

Vertical Gear Profile Grinding Machine

- On-board measurement system
- Automatic grinding with stock dividing
- Workpiece range: Ø50 mm ~ Ø600 mm
- Accuracy: AGMA Class 14 or DIN 4
- Fanuc Controller
- Luren designed Windows-based user-oriented interface
- Rotary table with direct drive torque motor

---

North American Sales Office: Luren Precision Chicago Co., Ltd. 1320 Tower Road, Schaumburg, IL 60173, USA Phone: 847-598-3555

Headquarters: Luren Precision Co., Ltd. 1-1 Li-Hsin 1st Road, Hsinchu Science Park, Hsinchu 30078, Taiwan Phone: +886-3-578-6767

Troubleshooting Problems

As well as upfront design of new products, another common reason for optimizing a design for NVH is when an existing design is put into a new application (a new vehicle model or paired with a new engine for example) and whine noise is found to be a problem. In a situation like this, there is very little scope for major design changes such as changing gearbox layout, tooth numbers, or number of planets. In these cases refining micro-geometry is often considered the only approach. An example optimization process based only on micro-geometry modifications is discussed here and illustrated with a real-world case study later.

The overall troubleshooting process is shown in Fig. 2. The first step is to identify the conditions under which the problem occurs. This is done by subjective evaluation in the vehicle. This is backed up by a quantitative measurement of noise and vibration both in the vehicle and on a test bench. The results of these tests form the baseline results against which the noise and vibration of the new design can be compared. If the test bench results show the same symptoms as the in-vehicle results, then all further simulation and testing can be performed in the more controlled environment of the laboratory. Analysis of these test results also yields information on which planetary gear set is causing the problem.

The next step is to create the RomaxDesigner model of the transmission. This model should represent as closely as possible the actual transmission tested and the boundary conditions should represent those of the test (in-vehicle or test bench). Typically this means that the micro-geometry of the gearbox being tested should be measured and the exact micro-geometry used in the model. Critical dimensions such as planet pin positions, housing bearing bore locations, and axial and radial clearances of critical compo-

---

**Fig. 4:** Components of the rear planetary gear set in the six-speed transmission.
nents should also be measured to ensure that they conform to the design specification. Ideally these measurements should be performed on a number of gearboxes from the production line to check manufacturing variability. If any components are out of tolerance (especially micro-geometry) then these manufacturing issues should be addressed first before any further investigation continues. In terms of boundary conditions, we need to simulate, at least approximately, the upstream and downstream rotary inertia and torsional stiffness as well as the support conditions for the gearbox housing.

The predictions from the model should be compared with the baseline test results to confirm that the model is recreating the symptoms of the original problem. This means we can be confident that any design changes we make in the virtual world will have the same effect in the real world and we can now proceed to the optimization phase.

It is important that the loading conditions we choose for the optimization do not just include those conditions where there is a gear whine problem. We also need to consider those conditions where the noise is not perceived to be annoying. This is to ensure that any design changes we make do not have a detrimental effect and we avoid the possibility of solving one problem but causing another.

The details of the optimization phase of the troubleshooting process are expanded upon in fig. 2. The heart of the process is a parametric sensitivity study where the most important parameters are varied and their effect on the contact pattern and TE identified. In the example shown we are only considering micro-geometry parameters, but other parameters could be assessed in the same way. Overall we are looking to reduce the TE of individual meshes and the combined TE of all meshes together while still maintaining a centralized contact pattern and acceptable surface stress to ensure durability is not compromised.

The sensitivity analysis is first performed on the planet-ring gear meshes and the revised micro-geometry is applied to the gears in the model (usually this micro-geometry is applied only to the planet gear as precise hard or soft finishing of an internal gear is difficult in a mass production environment). The same process is then performed on the sun-planet gear meshes and the revised micro-geometry is again applied. Now remember that one of the difficulties with simulating gear whine in planetary gears is that changes made to one gear mesh affect the performance of all gear meshes. This means that we have now have to go back and repeat the analysis on the ring-planet meshes again to see if these need revising. Theoretically we could repeat this iterative loop until perfect convergence was achieved, however in practice, one iteration is usually sufficient.

Of course our target for quantifying noise performance is not the TE and the contact pattern, but the housing vibration; so with the optimization phase complete, the final steps are to confirm that the new simulated vibration response for the optimized design is reduced to an acceptable level. This is then confirmed in the real gearbox by a one-off prototype test before production of the transmission with the revised gear design can be resumed.

CASE STUDY

In an SAE paper, Hyundai described how they used these methods to address a gear whine problem, in a six-speed planetary automatic transaxle gearbox, which was identified by subjective testing. Subsequent quantitative testing identified increased noise levels in the medium to high torque range (60 Nm-200 Nm), at engine speeds of 900 rpm-1300 rpm.

A complete gearbox model with detailed shafts, bearings, gears and housing was created (fig. 1). Radial clearances at the bushes and internal clearances of the bearings were calculated from the design tolerance, accounting for thermal expansion under operating conditions. Details of the actual test gearbox (clearances and measured micro-geometry) were used in the model for maximum simulation accuracy. Three load cases were used for the testing and analysis to cover the operating torque range. RomaxDesigner was then used to predict the vibration on the gearbox housing, the results of which compared well with measurements from the baseline test (fig. 3).

Analysis of the noise measurements showed that the rear planetary system was the source of the gear whine noise (fig. 4). This gear set is a reversing planetary arrangement comprising a sun gear, three inner and outer planet gears and a ring gear. The micro-geometry optimization process described above was applied to the gear set and a revised micro-geometry design was generated. Figure 3 shows a comparison of the predicted vibration response at one location for the baseline and optimized design. There is a clear and significant improvement predicted due to...
the recommended micro-geometry design changes. As a final proof of the validity of the optimized design, prototype gears were manufactured and installed in the transmission. The noise and vibration of the improved transmission was measured on the test bench, and the results in fig. 5 show a reduction of 6dB in the radiated noise in the problematic speed range and the required noise target was met.

CONCLUSION

Noise problems with complex machinery are always difficult to solve and gear whine in automatic transmissions is no exception. The methods demonstrated here clearly show that it can be done quickly and reliably provided the right tools are available. The key to success is to have the capability to model the complete transmission with sufficient detail and to account for the interactions between all components simultaneously. Combining this with fast computation times makes parametric design optimization a practical reality.

The case study presented here shows that these are not just hollow claims. To achieve a 6dB reduction in radiated noise from a gearbox while being restricted to only making changes to gear micro-geometry is a considerable achievement in a mass production environment.

Giving engineers tools like RomaxDesigner leads to improved product quality with reduced development times and costs not only when troubleshooting existing designs but also when creating a new gearbox from scratch. Clearly, designing out noise problems on the computer is faster and cheaper than waiting until the prototyping phase and in the case of a new product it usually leads to a better design rather than one that is compromised by remedial changes put in place to eliminate problems which are identified later on in the development process.

ADDITIONAL READING:


4) Parker, R G. “A Physical Explanation for the Effectiveness of Planet Phasing to Suppress Planetary Gear Vibration,”

ABOUT THE AUTHORS:


RIVERSIDE SPLINE & GEAR INC.
P.O. BOX 340 • MARINE CITY, MI 48039
PH: (810) 765-9302 • FAX: (810) 765-9595
deniset@splineandgear.com

Riverside Spline & Gear is your complete manufacturing facility, specializing in open gearing for many industries including machine tool, mining, forestry and oil and gas.

Riverside offers the quickest turnaround in the industry. After more than 45 years in business, our customers trust us for the highest quality and service, plus on time delivery, every time.

Over the last decade, we have invested millions of dollars on new machines and services to stay on the cutting edge of manufacturing solutions. At Riverside Spline & Gear, our commitment to innovation has put us on the preferred list of many leading global manufacturers.

JANUARY 2012 49