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Sensitivity analysis of gear whine noise in multistage gear box through multi body modeling

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Abstract

Quieter transmissions and improved NVH levels in passenger vehicles have become an important goal in automotive industry. Gear whine noise is one of the major contributors to overall vehicle NVH. Reducing gear whine noise to an acceptable level is a big challenge mainly due to weight reduction strategies to achieve better fuel economy, especially for multistage manual transmission gear box. CAE based noise prediction, mathematical analysis and mitigation strategies often deliver first time quality design product with low NVH target. This paper will discuss simulation techniques to investigate 3rd gear whine noise at full load condition with different micro geometry. The simulation work has been carried out using multi body simulation tool AVL Excite®. To do sensitivity analysis of third gear and common pair gear micro geometry and optimize the structural borne noise. The gear box geometric parameters and gear micro machining parameters are studied in detail. The surface velocity of structural housing contact pattern and transmission error are analyzed with different lead slopes of common gear pair.

Keywords: *Gear whine, Finite element model, Excite Power Unit, Surface velocity and Gear housing*

1.Introduction

The Gear whine noise is a major contributor to the overall transmission noise which makes human un-comfortability, and it is emitted from gears that are in mesh and the sound is characterized as structural vibration with frequencies same as the gear mesh frequency and its multiples [1]. The root cause of gear whine noise in manual transmission is force variation due to transmission error which cause some of the mechanical components to vibrate and these forces generally varies in amplitude and direction. These vibrations are transmitted via the shafts through the bearings to the housing and it excites the housing from which airborne noise is produced [2].

Structural vibrations are also transferred via housing mounts where they can excite other external components, such as parts of the compartment in a vehicle. One of the main sources of excitation in manual geared system is transmission error, Refer the section 2 for detailed description [3, 4]. The transmission error has also been identified as the primary cause of gear whine noise generation. Due to the twisting angle of the helical gear teeth, additional force components along the s-axial direction of shaft are also present as shown in figure 2. And it is required more attention on bearings, shafts, and design of gear housing [5-7]. Disadvantage of the helical gear is that due to the twisting angle of the teeth, additional force has been generated during the loading condition. Generally, the manual transmission vibration measurements involve high-cost equipment and testing methods. Several methodologies are in place from various Automakers to reduce the efforts of road testing and replace it with laboratory testing and math-based analysis. Simulations play a major role in the NVH performance as they use several mathematical models that make noise evaluation more precise and representative of in-use conditions [8].

Prediction of gear whine noise becomes an important concern in automotive industries. In many scenarios, it is very challenging for the noise engineer to come up with a right design modification for resolving gear whine noise issues, which irritates occupants even at low noise levels. CAE based noise prediction, analysis and mitigation strategies often deliver first time quality designs. There are three significant factors responsible for generation of noise and vibration by gear teeth. If the transmitted force between the teeth varies in amplitude, direction, or position, then gears will vibrate and generate noise. These actions occur when there is friction between the teeth, poor surface finish between matting gear, an imperfection in the tooth profile or a transmission error, which is relative motion between the gear teeth [9]

Estimation of the transmission noise induced from a vibrating structure is an important step for the design and development of a high-quality gear box. The dynamic responses to mesh stiffness variations for gears were numerically computed [10]. To correlate gearbox noise with structural parametric excitation, which are the function of misalignment, gear backlash and tooth deflections. The influence of the interior gearbox air -cavity on its vibratory dynamic response also studied and fluid structure interaction in the gear box was neglected and the model characteristics of the system are usually computed by considering only the mechanical properties of the structure [11-12]. The estimation of average surface normal velocities is very useful for comparison with experimental results: It allows the engineers to easily observe how a mechanism performs and helps in shortening the product design cycle without building it, and there by that saves a lot of money and time in the automobile industry

2.Theory

Simulation is to be a reliable tool in design and development of gears. The Hyper mesh® software is used for preprocessing of manual transmission such as gear box, shaft, gears and creating boundary condition etc., Multi Body Dynamic tool (MBD) called AVL Excite power unit® is used for dynamic simulation and post processing. The present methodology involves building 3D/2D simulation model of manual transmission, setting torque transfer path for each gear whine load case.

2.1 Transmission error

Theoretically, for two gears with infinite stiffness and perfect involute, the rotation of the output gear would be a function of the gear ratio and input gear. Due to both intended shape modification and unintended manufacturing errors, gears will be under motion error between the output gear relative to the input gear.

The meshing gear stiffness variation and subsequent transmission error often considered to be the primary excitation of gear noise and optimizing the transmission error is to minimize the gear whine noise. The definition of transmission error is “the difference between the actual position of output gear and the position it would if the gear drive were perfectly conjugate” as illustrated in figure 1.

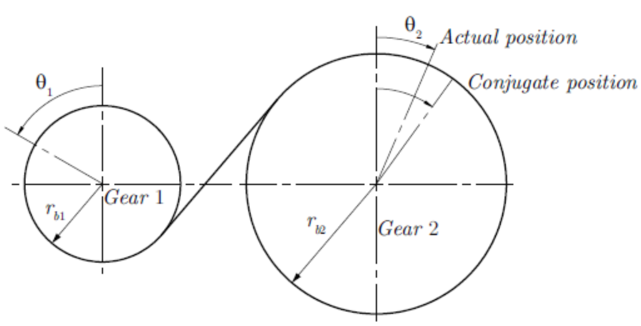


Figure 1: Illustration of transmission error

This difference can be expressed as an angular displacement in the position of the two gears according to equation 1

$$TE_{ang} = \theta_1 - \frac{r_{b2}}{r_{b1}}\theta_2 \quad (1)$$

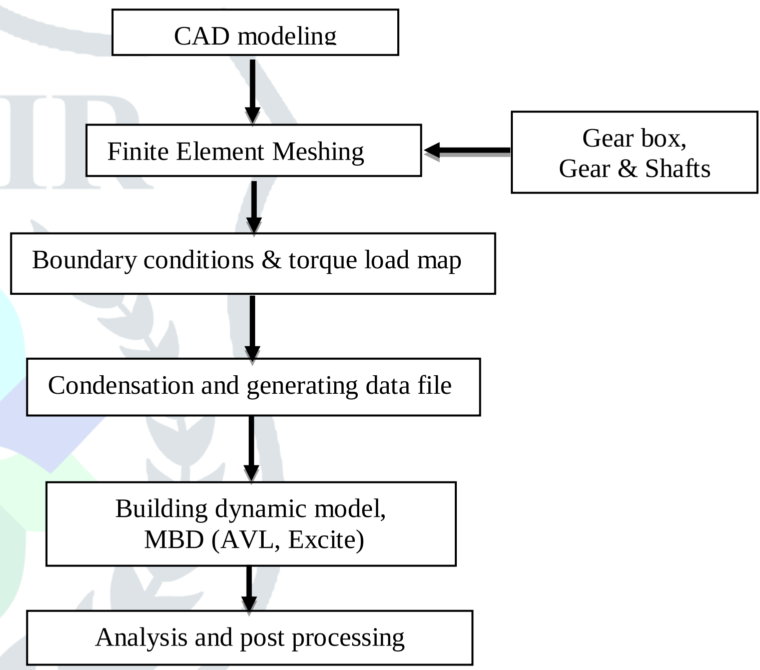
or as a linear displacement [11-12] along the line of action according to equation 2

$$TE_{lin} = r_{b1}\theta_1 - r_{b2}\theta_2 \quad (2)$$

Where r_{b1} and r_{b2} are the base radii and θ_1 and θ_2 are the angular positions of gear 1 and gear2 respectively (figure 1),

3.Simulation methodology

The simulation method involves two steps, in the first step the modal vector is calculated block. In the second step, the condensed mode shapes are used in the MBD model. In simulation, the following approaches are used to build the dynamic simulation model toto determine the structural vibration of gear housing.



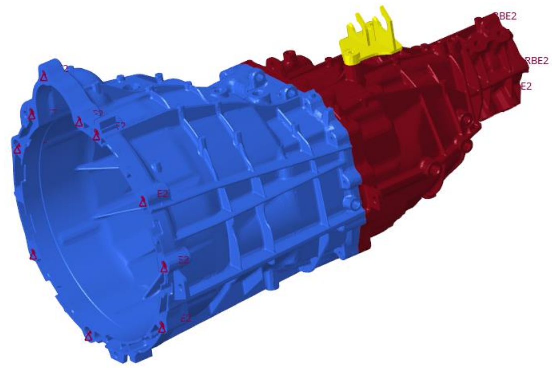
3.1 Problem description and modeling approach

The problem analyzed concerns a numerical study of the structure borne noise of six speed transmission. The surface velocity is a measure of NVH levels for a vibrating component. The velocities are often converted to dB levels, and the characterization are studied. This paper presents a modeling approach introducing gradually increasing complexity, starting from rigid body analysis, and introducing progressively the elastic behavior of the subsystem, using finite element modeling with modal analysis.

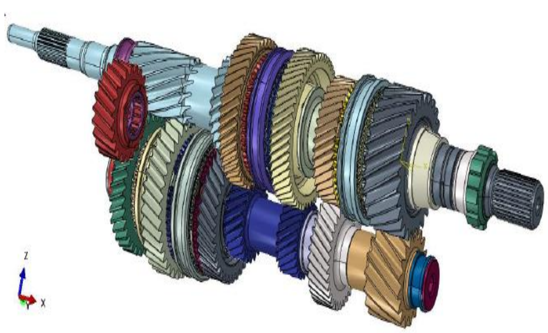
The originality of the overall approach is that it combines for a very complex system, the various numerical approaches with an experimental analysis of the system. Speed control approach is used to find speed loss factor of each gear engagement. This loss factors have calculated for every incremental speed with different load case such as part load and full load and it is used for gear whine prediction. The analyses are focused on drive gear whine for all gear with different load condition. In addition, the time dependent simulation results at the transmission housing, gears, shafts, and bearing are studied. A Multi- body dynamic simulation of the transmission was used to characterize it dynamic behavior, starting from input shaft rotation to countershaft through gear ratio. That counter shaft rotation finally reaches the output shaft through final drive ratio. In order to examine the vibration behavior of the input shaft, counter shaft, bearing and gears was specifically analyzed with a focus on vibrations, namely calculating the motion irregularities or transmission error, gear misalignment and extracting the surface velocity from transmission housing with different load case such as part load and full load.

3.2. CAD Modelling

Figure.2 shows representation of six speed manual transmission casing. The important geometric parameter quantity while designing gear box casing is ribbing stiffness which is to attain required strength. The present CAD Model of gearbox casing has total weight of 43 Kg including gears and shafts. The CAD model is imported by IGES file format to the FEM meshing software Altair Hyper mesh 11.0 ®.



(a) Gear housing



(b) Gears and shafts

Figure 2: Six speed transmission a) Gear housing b) Gears and shafts

3.3 Finite element meshing

The cad model in IGES format is imported in Hyper Mesh for the preparation of FE model. Then geometry cleanup was done by using options like ‘geom. Cleanup’ and ‘defeature’ to modify the geometry data and prepare it for meshing operation. Mesh model is prepared by using Hypermesh11.0. 2D Quad or tria meshing is carried out on all the outer and inner surfaces of the geometry, quads split to trias and then converted to tetras. 4-node Linear Tetra 3D solid elements are used to model of Gearbox. The element size selected for transmission Casing, input shaft, counter shaft and gears mesh is 10mm. Gearbox model is meshed with about 849534 nodes 496101 elements

3.4 Condensation

Condensation of multi DOF model to single DOF model and the simulation is very complex in nature; the mechanical systems often consist of several type elements with different of degrees of freedom which cannot be simplified easily as 1-dof models. To carry out NVH analysis and the dynamic modelling of a mechanical system with nDoF involves, numerous of analyses must be fulfilled to simulate the dynamic behavior of the mechanical components. The present transmission has very complex structure and consists of a lot of elements which may lead drive and coast rotation as well. On one hand, the components like gears consist of input shaft, countershaft, differential gear, and bearings have translation or rotational global motions and they must be considered. On the other hand, elements with both rotational and translation motions must be distinguished. In addition, the components may show linear elastic or rigid behavior, e.g., transmission housing, whereas connections of the bodies through bearing, must be handled via non-linear contact forces. To reduce the complexity of the system, it is particularly important that the system has to be broken down into sub-structures. Also, to analyses the dynamic behavior of all the sub-systems with accurate results, the sub-systems must be defined within the appropriate mathematical equations in the Excite power unit software.

3.5 Multi Body Dynamics systems

A multibody dynamic system (MBD) is the study of the dynamic behavior of a mechanism that consists of several rigid or flexible bodies and links which are connected to each other by joints to constraint their relative motions. Usually, the objective is to study how the mechanism behaves and moves under external loads. Here, we have studied the dynamic behavior of input shaft when it rotates under specific torque. This type of analysis is called forward dynamics. The problem can be also studied in a reverse manner: what kind of forces is needed to make a mechanism move in a specific way. This kind of analysis is called inverse dynamics [14].

3.6 Layout of the AVL excite power unit model

For this study, AVL Excite Power Unit module is chosen to simulate the six-speed transmission gear whine NVH analysis. The configuration of the 2D AVL Excite layout is illustrated in figure 3.

AVL Excite power unit component modelling which has wide range of joint models such as advanced gear joint, rigid body motion, spring damper models, gear contact and bearings, with linear or non-linear behavior. Also, it allows different possibilities for modelling of rigid and flexible mechanical components like shaft and joints. The standard 2D/3D models are available in AVL Excite's library and it can be used for building the gear whine simulation model. In this section, due to important roles of gear and bearing contacts, it will be discussed how they are modelled in AVL excite and the mathematical formulation of each joint model is extensively explained in AVL Excite manual [15]

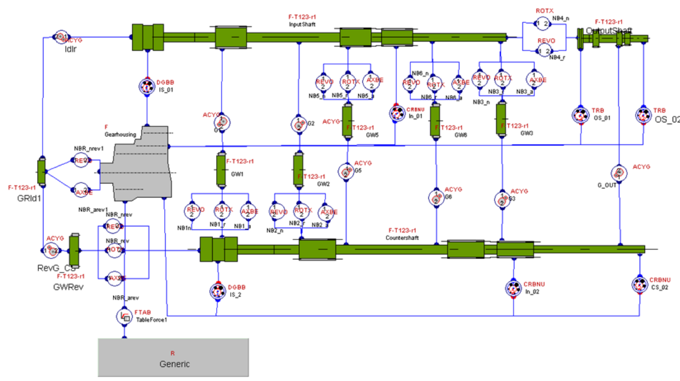


Figure 3: The 2D view of the AVL Excite power unit where y is the rotation axis and z are upward

The simulation model is consisting of six speed drive & driven gear wheel, one input shaft, one countershaft and output shaft, two deep grove ball bearing (DGBB), two taper rollers bearings (TRB) and three cylindrical roller bearings (CRB) as well as aluminum transmission housing. The material properties of aluminum are used for gear housing for gears and shaft the steel (20MnCr50) properties are used for this simulation. The bearings are in two end location of the shaft and also intermediate location to support the shafts via gear housing. The input shaft is connected with flywheel center point by using rotating pin joint. This rotating pin generates the required torque and angular velocity to simulate the different driving condition under part load and full load. The torque will be transferred from the input shaft to output shaft via countershaft. To reduce the given angular velocity, two levels of speed reduction provided by input shaft and counter shaft gears that leads to speed reduction. The details are given in the Table 1. This author takes gear ratio values from Table2 for the simulation.

Table1: Material Properties

S. No	Material Properties		E, Gpa	Poisson
1	Housing	AlSi9-F	71	0.33
2	Gears & Shafts	Steel	210	0.30

Table2: Total gear ratio

S. No	Total Gear Ratio	
1	Gear1	4.02
2	Gear 2	2.33
3	Gear 3	1.42
4	Gear 4	1.0
5	Gear 5	0.83
6	Gear 6	0.749

4. Result and discussion

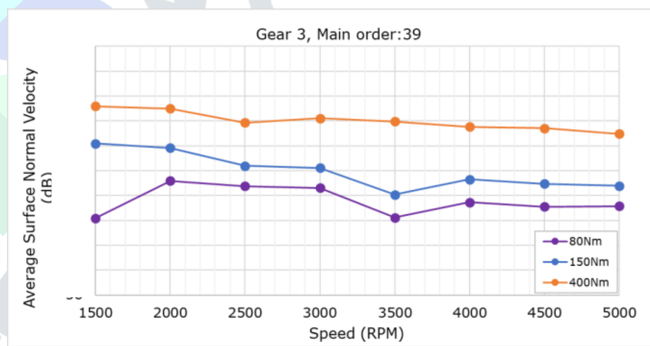
The following simulation cases (Table3) have been performed and third octave normal surface velocity results are obtained from the simulation and shown in figures.

Table2: Simulation of sensitivity analysis

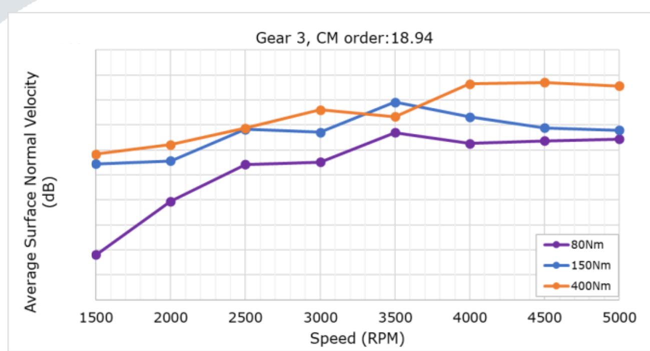
S. No	Case	Sensitivity analysis of Gear 3
1	Case1	Structural velocity at 80,150 and 400Nm
2	Case 2	Structural velocity at 400Nm with different CM gear Lead slope, 0µm,25µm,50µm
3	Case 3	Dynamic Transmission Error
4	Case 4	Contact pattern

Case1: Structural velocity at 80,150 and 400Nm

The total normal surface velocity results of third gear with different load condition such as 80Nm, 150Nm and 400Nm is shown in figure 4. In main order, if torque increases, the structure borne noise also increase over the speed which is clearly indicated in figure 4a. But in common pair gear order the structure borne noise slightly lower than part load at speed of 3500rpm which is shown in figure 4b. The maximum level of 3rd octave average surface normal velocity of third gear shown in figure 4c. Overall the structure borne noise is higher at maximum torque level in speed range from 3500 to 4000rpm



(a) Main order:39



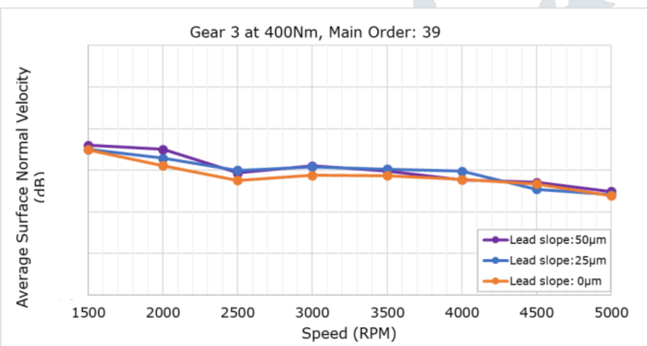
(b) Common Mesh :18.94

(c) Max level

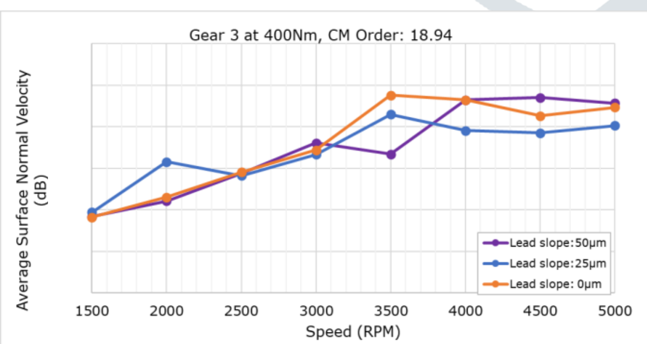
Figure 4: Average surface normal velocity a) Main order b) CM pair order c) Max level

Case2: Structural velocity with different lead slope at 400Nm

The structure velocity of third gear with different lead slope such as 0µm,25µm and 50µm at 400Nm is shown in figure 5. In figure 5a the lower lead slope predicts structural velocity comparatively lower than 50µm and 25µm. But in common pair gear the structural velocity is 8dB higher at 3500 rpm. Although, overall maximum surface velocity of 0µm lead slope is giving reasonable improvement at 3500rpm which is clearly viewed in figure 5c.



(a) Main order:39



(b)Common Mesh:18.94

(c) Max level

Figure 5: Average surface normal velocity with different lead slope a) Lead slope: 50µm b) Lead slope 25µm c) Lead slope 0 µm

Case3: Dynamic transmission Error with different lead slope at 400Nm

The transmission error of common pair with different lead slope at 400Nm shown in figure 6. The lead slope 0µm yields lower transmission error which is clearly indicate figure 6 and the surface velocity is indirectly proportional to transmission error. Overall, the good improvement in structure borne noise at lead slope 0µm.

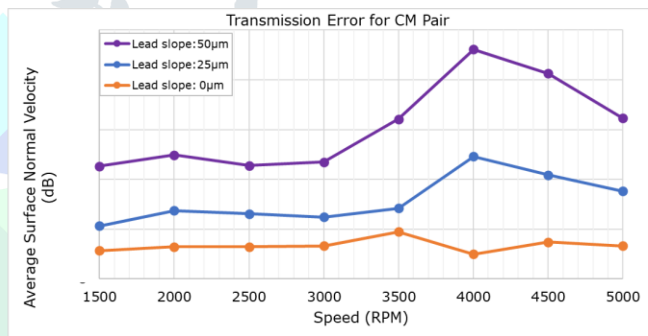
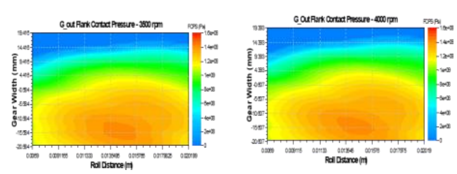
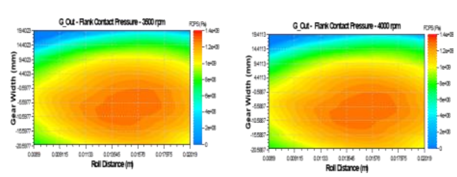


Figure 6: Transmission error for CM pair with different lead slope

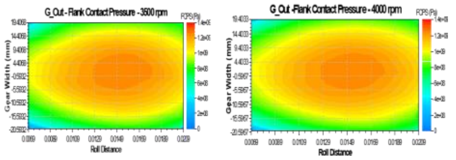
Case 4: Contact pattern with different lead slope



(a) Lead slope:50µm



(b) Lead slope:25µm



(c) (b) Lead slope:0µm

Figure 7: Common gear pair contact pattern at 3500 and 4000 rpm a) Lead slope: 50µm b) Lead slope 25µm c) Lead slope 0 µm

The contact pressure pattern is obtained for different lead slope of 50µm, 25µm and 0µm. The contact pattern for smaller lead slope is good compared to other common pair lead slope which is clearly shown in figure7

5.Summary/Conclusions

A systematic simulation approach has been performed especially for third gear with different load condition as well as various Common Mesh gear lead slope in manual transmission by using AVL Excite Power Unit and following conclusion are made.

- Reasonable improvement in structural velocity is obtained due to reducing lead slope from 50µm, 25µm and 0µm at full load condition.
- Significant improvement in transmission error is obtained due to reducing lead slope
- Good improvement in common mesh gear contact pattern is obtained at 3500 and 4000rpm especially lead slope 0 µm.

Finally, good improvement on 3rd gear whine noise while reducing lead slope on common gear pair

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