

Gear Rattle Noise Prediction from Dynamic Simulation

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ABSTRACT

Gear rattle noise is a common issue in manual gear transmissions and is often difficult to resolve. This paper discusses a methodology involving development of a simulation model for noise prediction and subsequent design of experiments (DOE) analysis to select optimal design parameters to reduce rattle noise. A one-dimensional torsional vibration simulation model for a tractor driveline was developed and was correlated with experimental measurements. This correlated model was used to calculate the torque variation between the gear pairs based on engine excitations. The standard deviation of this mesh torque was used as a metric and was correlated to noise ratings assigned by experts during experimental evaluation. Using this metric as the response variable, a DOE was conducted to determine the contributing factors and their influence on the rattle noise. Optimal design parameters were selected to achieve target value on the rattle metric. Physical prototype was built using these optimized parameters and was validated against noise ratings assigned by experts. It was found to successfully satisfy the subjective rattle criterion.

INTRODUCTION

Transmission noise is a major concern for any vehicle manufacturer because customers relate noise with quality. Gear rattle is one important source of noise in transmission systems and it is commonly observed in manual transmissions. It is caused by impacts between the teeth of unloaded gears traveling within their backlash. This becomes worse if the driveline natural frequency falls within the operating speed of the vehicle. In some cases the load

reversal can occur and it can introduce single or double sided gear impacts. The work described here discusses the simulation approach adopted to resolve the rattle noise. It is done for a manual shift agricultural tractor transmission, driven by a diesel engine and having gear rattle noise in operating speed range. The driveline uses a flywheel mounted clutch with an integral spring damper. The transmission and final drive gears connect it to the rear wheels.

The purpose of a transmission is to provide multiple ratios between the input and output. Typically these are simply referred as *gears*; however, where the discussion is about individual gear pairs, we find it necessary to describe the gears as *selected gear ratios*. Further discussion describes different models used in this exercise. The first one is the simulation model built for transmission dynamic analysis. Second is the regression model, obtained from initial DOE study and finally, the non linear regression model obtained from damper DOE.

SIMULATION MODEL

A torsional system model was developed in Msc Easy5 software. This is a one degree of freedom i.e. rotational system model. Initial modal analysis was done with a lumped mass system. It showed that the engine firing frequency would excite the transmission input shaft natural frequency within operating speeds. While the stress levels were of no concern, it had potential to contribute to gear rattle noise. To understand this further a detailed transmission model was built. [Figure 1](#) shows the layout of the driveline that was simulated. Following components are included in the simulation model.

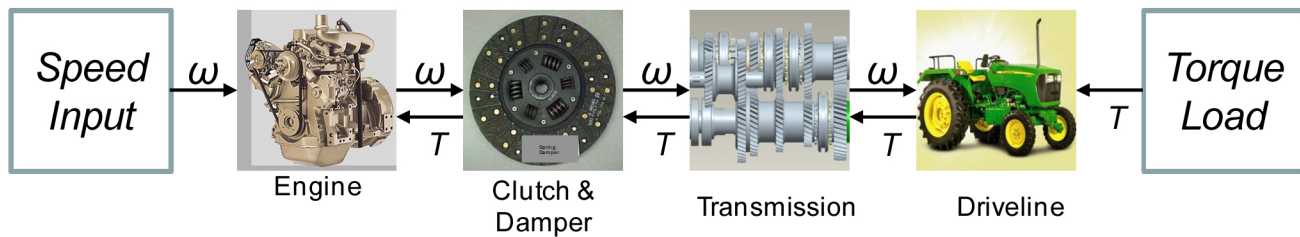


Figure 1. Drivetrain Model for the System Simulation

Table 1. Ratings for subjective evaluation of noise

Definition	Excellent	Very Good	Good	Fair	Adequate	Marginal	Poor	Bad	Very Bad	Atrocious
Rating	10	9	8	7	6	5	4	3	2	1

Engine: The engine dynamic model consists of number of cylinders, cylinder size, firing order and internal inertia distribution. This properly represents the engine's cylinder pressures to correctly replicate the engine's speed and torque response to applied load.

Clutch: This consists of inertia and the non-linear stiffness curve. The damper hysteresis was modeled as damping torque vs. angular velocity.

Transmission: This included gear pairs, with their backlash and the shafts with their properties: inertia, stiffness, structural damping. The gear backlash was modeled as a very stiff shaft with looseness (angular displacement) connecting the drive gear to driven gear. The torque within this shaft represented the load on the gear teeth.

Driveline: The remaining driveline consists of final drive gears, differential, axle shaft, tire stiffness and vehicle inertia. A dynamometer sub-routine was used to provide torque load at the wheels.

The Easy5 model was considered correlated when the input shaft torque waveform in a speed sweep matched the physical measurements. During correlation the model was adjusted with appropriate gear backlash within its tolerance zone, damping and tire stiffness values. Appropriate drag torque was also applied on the transmission shaft which represented the drag from the lubrication oil.

RATTLE NOISE PREDICTION APPROACH

Subjective evaluation: A team of experts evaluated the rattle noise levels and assigned ratings according to [Table 1](#). These evaluations were done at various operating conditions: engine speed, load, selected gears. One gear was rated poor, and another was very good, out of possible gears for this tractor. These are hereafter referred to as *noisy* and *silent* gears respectively.

Prediction of torque variation: The above Easy5 model was used to predict the torsional loading between the gear pairs. Torque impulses correspond to the gear impacts. In some cases it was observed that the gear pair had single sided impacts and in some cases it had double sided impacts. This transmission included six gear pairs and the torque variation was predicted for each gear pair. The rolling resistance was the only load in the model, applied at the wheels.

In order to check if the simulation model predicted any noticeable difference, the simulation was run with a noisy selected gear and a silent gear at constant engine speed. [Figure 2](#) shows that the torque variation of the noisy gear had greater amplitude than the silent gear. It also had more impacts. This agreed with the subjective evaluation. In the subjective evaluation the rating was the cumulative effect of the noise from six gear pairs. The simulation evaluated the individual gear pairs and all gear pairs were evaluated for the correlation.

Metric: The model correlated to the subjective evaluation and it was necessary to come up with a metric to quantify predicted mesh torque variations. Various metrics were calculated but the standard deviation (σ) of this mesh torque variation showed considerable separation between the noisy and silent gears. The simulation then was run in various selected gear ratios with the same time step and the same simulation time. The number of points considered for the standard deviation calculation was the same. The standard deviation correlated with the subjective evaluation. Refer to [Table 2](#) for the comparison between noisy and silent gears.

The standard deviation metric correlated with the noise levels, now the question was to know target values for acceptable gear rattle levels. The targets were selected to be close to the silent gears.

DESIGN OF EXPERIMENTS

Once the Easy5 model was created and considered accurate enough to be useful, the next step was to determine the values

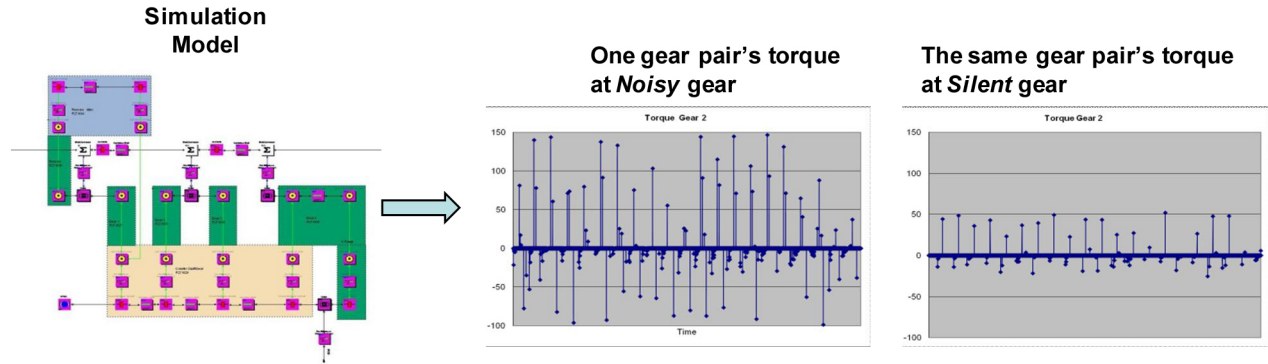


Figure 2. Comparison of torque prediction at a gear pair

Table 2. Comparison of subjective drive evaluation ratings, standard deviation of torque at meshes and their target values

Subjective Rating	
Noisy Gear	4
Silent Gear	9

Standard Deviation of Mesh Torque (σ) – Simulation Prediction						
Description	Tq_Gear1	Tq_Gear2	Tq_Gear3	Tq_Gear4	Tq_Gear5	Tq_Gear6
Noisy Gear	11.73	6.5	5.57	14.58	5.74	7.76
Silent Gear	12.6*	1.8	1.24	2.7	1.95	3.00
Target	4.00	3.00	3.00	5.00	3.00	3.50

- Greater std. dev. values signify a greater number and/or intensity of gear impacts
- *Gear pair is loaded

Table 3. DOE Factors

Factors	Levels	Description
Flywheel inertia	100%, 150%, 200% of existing design	
Gear Backlash	0.05, 0.25, 0.5 mm	All the gear pairs were tied to one backlash value
Top Shaft Gear Inertia	50%, 100%, 200% of existing design	All the gear inertia values were proportionally varied
Countershaft Gear Inertia	100%, 200%, 300% of existing design	
Countershaft Drag	100%, 250%, 400% of existing design	
Damper Stiffness		Considered different designs e.g. one stage design, two stage design
Damper Hysteresis	100%, 250%, 500% of existing design	

of those parameters that would reduce the rattle to an acceptable level. This model was most accurate; however it was non-linear and it took ten minutes for each run. Optimization from the simulation would be painfully slow unless a faster model was obtained. We set out to develop a simplified model (regression model), one that might not be quite as accurate or might be accurate under limited conditions, but would be so much faster that one could quickly optimize the parameter settings. This was done by exercising the simulation model by means of several designs of experiments.

This section discusses the procedure that was used to learn how modifying the parameters affected rattle. For the investigation, the noisy selected gear ratio was used. As before the rolling resistance was the only load and the simulation was run at constant engine speed.

Initial DOE: The factors responsible for rattle are well known, but their relative contributions and the values they needed to be in order to sufficiently reduce the gear rattle, was not known. First a general DOE was run to establish an overall perspective of the factors. These factors and their levels are listed in the [Table 3](#).