

Characterizing the Onset of Manual Transmission Gear Rattle Part I: Experimental Results

Darrell Robinette, Randall S. Beikmann, Paul Piorkowski and Michael Powell
GM Powertrain

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ABSTRACT

The objective of this investigation is to characterize the ability of loose gears to resist rattle in a manual transmission driven by an internal combustion engine. A hemi-anechoic transmission dynamometer test cell with the capability to produce torsional oscillations is utilized to initiate gear rattle in a front wheel drive (FWD) manual transmission, for a matrix of operating loads and selected gear states. A signal processing technique is derived herein to identify onset of gear rattle resulting from a standardized set of measurements. Gear rattle was identified by a distinct change in noise and vibration measures, and correlated to gear oscillations by a computed quantity referred to as percent deviation in normalized gear speed. An angular acceleration rattle threshold is defined based upon loose gear inertia and drag torque. The effects of mean speed, mean and dynamic torque, and gear state on the occurrence of loose gear rattle are reported. The second paper of this two part series discusses analytical modeling of gear rattle and the effects of parameters not easily modified or controlled through hardware testing.

INTRODUCTION

Gear rattle in a manual transmission is a result of angular velocity fluctuations introduced by the combustion process in a reciprocating engine. The torque pulses excite angular motion of the entire driveline. The

resulting speed fluctuations are imposed on all the gears in the power flow. Loose gears corresponding to gears coupled to the powerflow, but not active in torque transfer, have the potential to rattle. The motion of a loose gear is not completely governed by the dynamics of the driving gear, but also by its other interfaces. As the driving gear decelerates, it cannot pull the loose gear; thus to maintain contact, the loose gear must have adequate drag torque to decelerate it at the same rate. If the loose gear decelerates at a slower rate than the driving gear, contact is lost, leading to an impact which occurs as the teeth of the two gears regain contact (either on the drive or coast side). The drag torque on the loose gear is a function of gear design, oil immersion depth, oil properties, bearing design and operating condition. A simplified diagram governing the gear rattle threshold is provided in Figure 1.

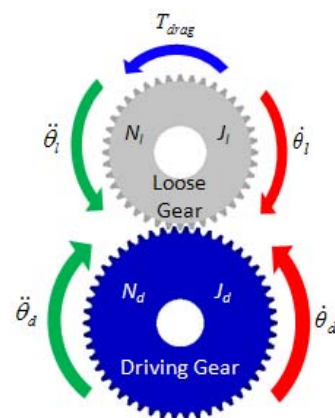


Figure 1. Diagram of loose gear rattle

As mentioned, the level of drag torque determines whether the angular motion of the driving gear causes loss of contact between it and the loose gear. Three drag torque ranges exist: 1) the torque required to decelerate the loose gear is less than the drag torque, 2) the torque required to decelerate the loose gear is nominally equal to the drag torque, and 3) the torque required to decelerate the loose gear is greater than the drag torque. The torque required to maintain contact is the product of loose gear inertia and its angular acceleration. This quantity will be referred to as inertia torque. The three ranges of drag torque and rattle are summarized in Equations 1a through 1c, respectively.

$$\text{No Rattle:} \quad J_l \ddot{\theta}_l < T_{drag} \quad (1a)$$

$$\text{Incipient Rattle:} \quad J_l \ddot{\theta}_l = T_{drag} \quad (1b)$$

$$\text{Rattle:} \quad J_l \ddot{\theta}_l > T_{drag} \quad (1c)$$

Any resulting gear rattle will fall into one of three categories:

- 1) Continuous single-sided,
- 2) Continuous double-sided, or
- 3) Intermittent.

Gear rattle is manifested as a broadband air borne noise from two distinct mechanisms. While some noise is directly radiated by the gears, the primary mechanism is vibration propagating through the structure of the transmission, causing vibration of the transmission case surface, which then radiates noise. Because of the “filtering” by the radiation efficiency of the transmission case, the noise spectra will have different frequency content than the case vibration. Airborne rattle noise is typically more noticeable in the vehicle than from any structure borne path through the powertrain mounts.

Rattling of loose gears within a transmission can be evaluated and defined by a variety of techniques and methods. Experimentally, rattle can be determined through objective or subjective data and analysis procedures [1, 2, 3 and 4]. Dynamometer or vehicle testing has primarily been limited to examining the individual effects of input speed, excitation frequency, inertia and viscous drag; see [1 and 4]. Some researchers (see [4 and 5]) have used gear speed data to produce specific metrics to detect the absolute point at which gear teeth impacts first occur. Objective measures usually involve non-intrusive measures, such as case vibration or radiated noise, which are then evaluated using psychometrics to determine what set of operating conditions rattle create an annoyance. Correlation between subjective and objective measures of gear rattle was achieved by Forcelli et al. 2004 and

applied to an SAE rating scale. Analytically, a global powertrain/driveline or localized gear mesh perspective can be taken. In the global powertrain/driveline model, the effect of individual component changes can be evaluated in terms of the resulting angular motions imposed on the driving gears. The influences of clutch properties, spring rates and hysteresis on loose gear rattle have been explored in [6, 7, 8 and 9]. In general it was found that lower spring rates and hysteresis for the first stage springs in a single mass flywheel help to improve idle rattle. The benefit of a dual mass flywheel for reducing rattle was shown in [6]. The factors controlling rattle at the gear mesh, particularly tribological effects, were studied and reported in [10], [11], and [12]. To date, a comprehensive look at how operating conditions, gear state, and their interaction influence the onset of gear rattle for all loose gears has not been reported.

The purpose of this two-part investigation is then to quantify the onsets of gear rattle for individual loose gears, for a matrix of operating conditions. Part I here discusses the experimental setup, noise and vibration measurements, and a methodology developed to process measured gear speed data to determine the occurrence of rattle and the applicability of a rattle threshold metric. Part II focuses on using the experimental data and data processing methods from this paper to develop and validate a lumped parameter analytical model. Details regarding estimation of drag torque acting on each loose gear are provided. Part II will also examine the effects of various design parameters and their influence on the inception of gear rattle.

EXPERIMENTAL SETUP

DYNAMOMETER SETUP

A hemi-anechoic transmission dynamometer test cell was used to test a FWD manual transmission for gear rattle using a standardized test procedure. The test cell consists of a 260 kW AC dynamometer to drive the test transmission and two 300 kW AC dynamometers to absorb power from the test transmission. Semi - rigid shafting couples the drive dynamometer to an inline rotary torque meter followed by the flywheel and clutch damper of the transmission. The transmission structure is attached to a rigid fixture at the bell housing surface. Half shafts and an intermediate shaft couple the final drive of the transmission, through inline rotary torque meters, to the absorbing dynamometers (see Figure 2). Torque was recorded from each inline torque meter and speed from the shaft encoders at each dynamometer.

to rattle. Design detail of the individual gear pairs is provided in Table 2.

Table 1. Test transmission loose gears by selected gear

Engaged Gear	Loose Gear						
	1st	2nd	3rd	4th	5th	Rev Idler	Rev Drivin g
Neutral Fixed	X	X				X	
Neutral Rolling	X	X	X	X	X	X	X
1st		X	X	X	X	X	X
2nd	X		X	X	X	X	X
3rd	X	X		X	X	X	X
4th	X	X	X		X	X	X
5th	X	X	X	X		X	X
Reverse		X	X	X	X		

X = Gear may rattle

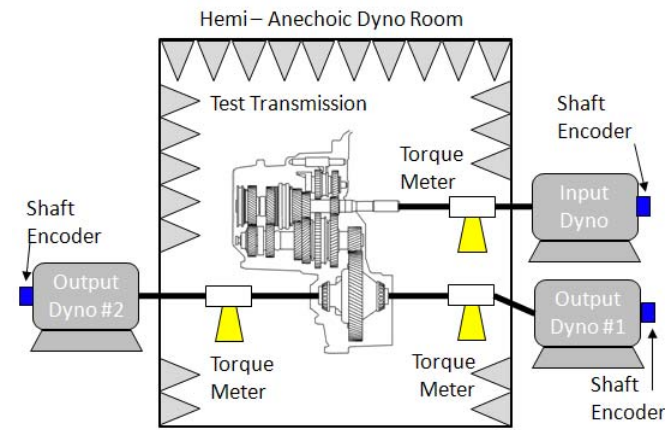


Figure 2. Schematic of hemi – anechoic transmission dynamometer test cell arrangement

Control of the test cell is achieved through an MTS Advanced Dyno Controller and customized MTS dyno control software. A unique feature of this dynamometer is the ability to add a dynamic speed or torque input onto the mean speed or torque of any of the three dynamometers. The resulting angular motion and torque at any point are thus represented as in Equations 2a and 2b:

$$\dot{\theta} = \dot{\theta}_m + \dot{\theta}_d \sin[(2\pi f)t] \quad (2a)$$

$$T = T_m + T_d \sin[(2\pi f)t] \quad (2b)$$

Where the subscript *m* denotes the mean component and the subscript *d* denotes the amplitude of the dynamic component.

TEST TRANSMISSION

The transmission tested in this investigation was a synchronized five speed FWD manual transmission with a maximum torque rating of 353 Nm. A top-down cross section view of the test transmission is shown in Figure 3. The transmission was coupled to the drive dynamometer through a single mass flywheel/pressure plate/clutch assembly with a three stage clutch damper (torsional properties can be found in Part II). The driving gears for first and second gear are machined into the input shaft, while those for third, fourth and fifth gears ride on needle bearings and are driven through synchronizers. The driven first, second, and reverse gears are synchronized to the output shaft. The driven third, fourth and fifth gears are splined to the output shaft. The driving gear of the final drive is a machined component of the output shaft. The primary reverse stage driven gear is splined to the reverse idler shaft, while the secondary reverse stage driving gear is synchronized to the same shaft. Table 1 is a matrix for the gear states for all power flows, denoting with an “X” which gears are loose, and therefore have the potential

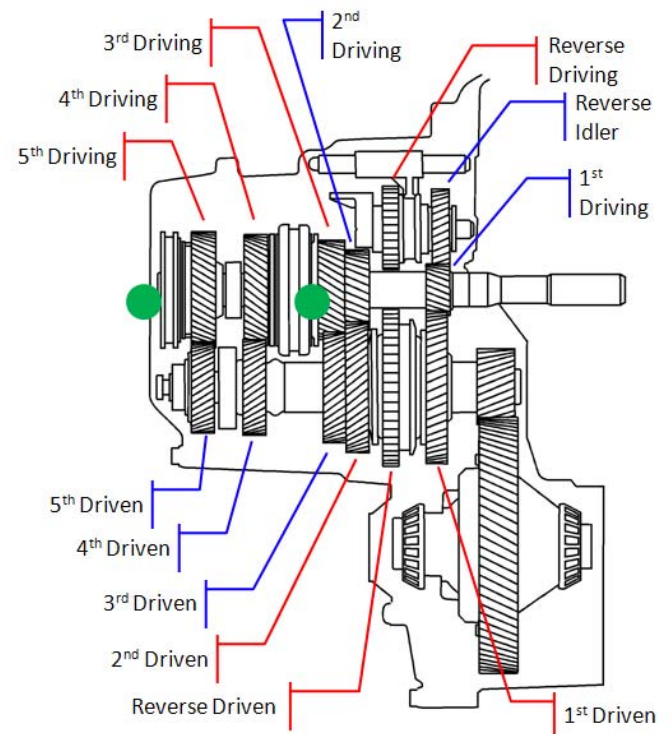


Figure 3. Transmission top-down cross section view indicating magnetic pickup gear naming convention (blue = driving gears, red = loose gears) and location of microphones and accelerometers (green circles)

Table 2. Test transmission gear design details

Gear	Teeth Driving	Teeth Driven (loose)	Module	Pressure Angle (°)	Helix Angle (°)	Total Contact Ratio
1st	13	44	2.40	20.0	25.0	1.96
2nd	25	44	1.95	17.0	28.0	2.05
3rd	39	46	1.52	17.0	32.5	3.75
4 th	47	42	1.46	16.5	32.0	3.87
5 th	54	38	1.42	17.0	32.0	3.77
Rev 1	13	21	2.40	20.0	25.0	1.80
Rev 2	25	49	2.45	20.0	0.00	1.05
FD	21	85	2.06	18.0	30.0	4.02

MEASUREMENTS

Gear Speed

Each gear of the test transmission was instrumented with a Hall Effect magnetic pickup to acquire instantaneous gear speed, with the objective of detecting incipient rattle. An access hole for each sensor was drilled into the transmission case centered with the measured gear, and tapped for threads. Each magnetic pickup was installed with a nominal air gap of 0.381 mm to ensure a consistent signal. Figure 3 shows the arrangement of magnetic pickups and the naming convention of all instrumented gears used for Parts I and II of this paper.

Noise and Vibration

Measurements were made of nearfield acoustic pressure and transmission case vibration, to comprehend the effect of gear rattle on perceived noise and vibration metrics. These data were also used to correlate to the onset of gear rattle as determined by the gear speed measurements mentioned previously. Two free field condenser microphones were placed 10 cm from the transmission housing top and end cover surfaces, while two uniaxial accelerometers were placed on these same surfaces. The approximate location of the microphones and accelerometers are indicated in Figure 3 by the solid circles.

TEST PROCEDURE

A matrix of test conditions (shown in Figure 4) was developed to determine the effect of operating condition and selected gear state on the inception of loose gear rattle and the influence on perceived noise and vibration

metrics. The intent was to minimize the number of dynamometer test conditions, but yield a sufficient amount of data to quantify the interaction of the steady operating condition, gear state and torsional excitation on gear rattle. The selected operating conditions encompass a typical operating range where gear rattle is most likely to occur (Table 3). For each operating condition, a set sequence of torsional amplitudes was imposed upon the test transmission, sweeping from low to high amplitude.

Dynamic torque is used as the source of torsional excitation instead of dynamic speed fluctuation, to more accurately represent combustion torque pulsations produced by the internal combustion engine. The dynamic torque amplitudes represented in the results section are unique to the test sequence and the dynamometer setup. Even though dynamic torque is the controlled source, it is the resulting speed fluctuation produced at a loose gear that leads to the loss of gear tooth contact.

The dynamic torque applied during the test sequence was controlled by a PID feedback loop within the input dynamometer controller. This dynamometer controller can only apply a single frequency, constant amplitude dynamic torque in a given operating condition, so it was not possible to continuously sweep either its frequency or amplitude. Thus, each torsional test sequence was executed in a series of conditions, each with a fixed frequency, mean input speed and output torque. During each test sequence, the dynamic torque was applied at some initial amplitude, stopped, and then applied at successively higher amplitudes. In this manner a pseudo-sweep of dynamic torque amplitude was obtained (see Figure 5). The initial dynamic torque amplitude for each sequence was ± 10 Nm and the final amplitude was ± 200 Nm. Each torsional step was 4 seconds in duration, followed by a 2 second pause to stop and restart the dynamic torque control loop. A total of twenty torque levels constituted each test sequence. Note that the mean input torque has been removed from Figure 5 for clarity of the dynamic torque amplitudes used in each torsional step.

Table 3. Range of operating conditions tested

Parameter	Low Value	High Value
Input Speed (rpm)	900	2750
Excitation Order	2	4
Excitation Frequency (Hz)	16.67	91.67
Input Torque Driving (Nm)	50	200
Input Torque Coasting (Nm)	135	135