

Vibro-Impact Analysis of Manual Transmission Gear Rattle and Its Sound Quality Evaluation

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ABSTRACT

Experimental schemes, frequency characteristics, subjective and objective sound quality evaluation and sound quality prediction model establishment of a certain mass-production SUV (Sport Utility Vehicle, SUV) manual transmission gear rattle phenomenon were analyzed in this paper. Firstly, vehicle experiments, including experiment conditions, vibration acceleration sensor and microphone arrangements and especial considerations in experiments, were described in detail. Secondly, through time-frequency analysis, broadband characteristics of manual transmission gear rattle noise were identified and vibro-impact of gear rattle occurs in the frequency range of 450~4000Hz on the vehicle idle condition and the creeping condition. Thirdly, based on bandwidth filtering processing of gear rattle noise, subjective assessment experiments by a paired comparison method were carried out. Evaluation results passed triangular loop verification and Spearman correlation coefficient examination, and then subjective annoyance results of each noise sample were calculated. Further, objective evaluation results, based on two physical acoustics parameters and six psychological acoustics parameters, were obtained respectively. Finally, comprehensive evaluation of subjective and objective results was analyzed by the MLR (Multiple Linear Regression, MLR) method. It's concluded that AI (Articulation Index) was the appropriate parameter that's closely related to subjective annoyance results, and correlation coefficient of AI and subjective annoyance results was up to 0.948. Sound quality prediction model of gear rattle was then established on the vehicle idle condition and the creeping condition. Overall in this paper, research achievements could be adopted to solve practical engineering problems (especially gear rattle problem), and furthermore it could reduce R&D (Research and Design, R&D) cycle, labor costs and material costs dramatically.

CITATION: Wu, G. and Wu, H., "Vibro-Impact Analysis of Manual Transmission Gear Rattle and Its Sound Quality Evaluation," *SAE Int. J. Commer. Veh.* 10(1):2017, doi:10.4271/2017-01-0403.

INTRODUCTION

Vehicle powertrain noise, vibration and harshness (NVH) have attracted more and more attentions from automotive companies and research institutions around the world. Vehicle powertrain includes many torsional systems and has the possibility to create annoying noise and undesirable vibration. The engine, as a power source, produces a fluctuating torque [1]. Because of the torque fluctuations, the shafts of manual transmission are subject to torsional vibration, and this induces idle gears to bounce against each other in the circumferential backlash. Even though small, the backlash is necessary for the functionality of the gear set to allow lubrication of the teeth during contact and avoid them seizing. Gear bouncing against each other could produce rattle noise. Gear rattle noise could make passengers disturbed easily and consider that manual transmission may have trouble mistakenly. Characteristics identification and sound quality evaluation of gear rattle noise appear particularly important.

Vehicle experiment or bench tests are effective measures of gear rattle research and there're many research achievements. As for bench test, Crowther A.R et al. set up a test rig for gear rattle and the rig was designed to provide sufficient excitation across typical engine idle speeds. But design maximum torque for transmission input shaft

peak-to-peak vibration just was 2 Nm and it was circumscribed to simulate engine speed torque fluctuation [2]. Couderc et al. designed and built early an experimental setup of a vehicle driveline for the prediction of the dynamic behavior of a vehicle driveline system. It is concluded that the simulation model validated by the experimental setup could provide transient response truly [3]. Bellomo et al. analyzed the contribution of individual sound source to the overall rattle noise by means of noise source analysis and proposed a pareto-optimal solution to reduce the rattle noise emission, utilizing a rattle test bench [4]. This improved test bench reproduced the branched driveline system, rather than the one-string driveline system in Ref. [3]. Forcelli et al. set up a virtual engine simulator for automotive transmission and conducted a parametric sensitivity study for amplitude of the torsional vibration. Moreover, a relationship between the vibro-acoustics measurements and the human perception was found [5]. Brancati et al. set up a specific test rig for one lightly loaded gear pair, which is able to acquire the relative rotation motion of gears by two high resolution incremental encoders. Based on measurement data from this test rig, a gear rattle metric based on the wavelet multiresolution analysis was proposed [6].

From vehicle experiments, Prasad, J.S et al. found that maximizing the clutch could attenuate the vibration peaks observed on clutch housing, which are then transferred to driveline system and cause gear rattle noise [7]. Xu Xuchu et al. presented a novel clutch damper with three-staged stiffness. The results of vehicle test showed the three-staged stiffness clutch damper has better vibration attenuation effects than the two-staged stiffness, especially on the vehicle creeping condition [8]. It's obvious that the clutch damper plays an important role in improving the driveline vibration and gear rattle problem. Xiong T et al. identified structural transfer paths as the major noise transfer paths for gear rattle noise and improved transmission gear rattle phenomenon through adjusting structural transfer paths such as clutch cable and gear shift cables [9].

Above all, bench test and vehicle experiment focuses on the mechanism of gear rattle. However, research achievements about sound quality of gear rattle noise are scarce. The aim of this article is to analyze gear rattle noise characteristics, evaluate gear rattle noise subjectively and objectively, and establish a sound quality prediction model of gear rattle noise. Firstly, experimental scheme of manual transmission gear rattle phenomenon, which includes the experiment driving condition, sensor arrangements and special attentions, would be represented. Secondly, noise characteristics of manual transmission gear rattle is analyzed by time-frequency results of vibration acceleration and sound pressure. Frequency range of gear rattle noise would be discussed. Thirdly, based on bandwidth filtering processing of gear rattle noise, subjective assessment experiments by a paired comparison method are carried out and subjective annoyance results of each gear rattle noise sample are calculated. Further, based on two physical acoustics parameters and six psychological acoustics parameters, objective evaluation results are obtained respectively. Finally, correction analysis of subjective and objective evaluation is investigated, and comprehensive sound quality prediction models are established by the MLR (Multiple Linear Regression, MLR) method.

VEHICLE EXPERIMENT SCHEME OF MANUAL TRANSMISSION GEAR RATTLE PHENOMENON

Introduction of Vehicle Parameters and Manual Transmission Structure

A certain mass-production SUV (Sport Utility Vehicle, SUV) is taken as the research object and its fundamental parameters are listed in Table 1. The vehicle is equipped with a twin-shaft and 6-speed manual transmission and its specific structure is as shown in Figure 1. The manual transmission includes six forward gears and one reverse gear. The driving gears for first and second gear are machined into the input shaft, while driving gears for third, fourth, fifth and sixth gear are assembled on needle bearings and are driven through synchronizers on the input shaft. The driven first and second gears are synchronized to the output shaft. The driven third, fourth, fifth and sixth gears are splined to the output shaft. The driving gear of the final drive is machined into the output shaft. For reverse gear, the

driven gear of first gear is as the driving gear and the driven gear of reverse gear is synchronized to the reverse gear shaft. The other gear on the gear shaft drives the driven gear of the final drive. When manual transmission is in 1st gear, driving and driven gears of 2nd gear, 3rd gear, 4th gear, 5th gear, 6th gear and reverse gear tend to produce rattle noise.

Table 1. Lists of fundamental vehicle information and parameters

Name	Parameter values or type
Vehicle type	SUV
Vehicle mass	1370 kg
Drive mode	Front-engine Front-drive
Transmission Type	6-speed manual transmission
Engine displacement	1.5 L
Engine air intake mode	Turbocharging
Engine maximum power	100kW (@5500 r/min)
Engine maximum torque	220Nm (@1800~3500 r/min)

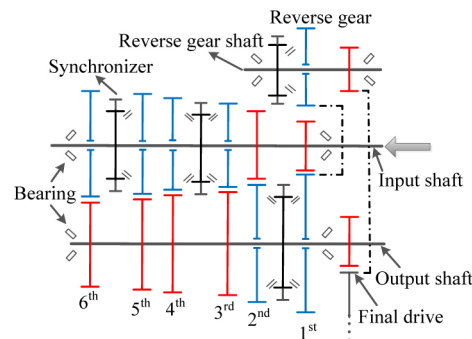


Figure 1. Specific structure for a twin-shaft and 6-speed manual transmission

The Experiment Condition and Sensor Arrangements

For vehicle noise performance evaluation at the final validation phase of vehicle development, it's found that gear rattle of manual transmission is severe on two low load-torque conditions, which include: (1) vehicle idle condition: engine rotates at idle speed, manual transmission is in neutral gear, and the gas pedal is released completely (2) vehicle creeping condition: engine rotates at a certain speed, manual transmission is in first gear, and the gas pedal and the brake pedal are released totally.

Vehicle experiments are carried out on flat and straight road and in open and low background noise environment. Professional data acquisition equipment, as shown in Figure 2, is adopted. The data acquisition equipment is used for sound pressure acquisition and vibration acceleration acquisition. In vehicle experiments, adopted sensor type and its layout on the vehicle are presented in Table 2 and in Figure 3. Vibration acceleration sensors are located on bearing pedestal of the input shaft (as shown in Figure 3(a)) and on the middle part of transmission housing (as shown in Figure 3(b)) respectively. Microphone is placed in 30 cm distance from and right in front of the vibration acceleration sensor on the middle part of transmission housing (as shown in Figure 3(c)), and double-ear headphones are equipped on the driver's head (as shown in Figure 3(d)).



Figure 2. Data Acquisition Equipment for vehicle experiments

Table 2. Lists of sensor type and layout in vehicle experiments

Number	Sensor type	Sensor location
1#	tri-axial acceleration sensor	bearing pedestal of input shaft
2#	tri-axial acceleration sensor	Middle part of transmission housing
3#	microphone	Near middle part of transmission housing
4#	Double-ear headphones	Driver's ear



Figure 3. Vibration acceleration sensor and microphone sensor arrangements in experiments

During vehicle experiments, some considerations should be paid more attention to: (1) in the processing of sensor arrangements, greater and flatter plane on the transmission housing should be selected for sticking sensors, and the location should be far away from high-temperature service, for example engine exhaust pipe in case that sensor and wiring harness may be destroyed (2) vehicle experiments should be carried out in good weather and in the circumstance of no wind or breeze. Simultaneously, vehicle doors and windows are demanded to be closed totally, and auxiliary equipment on the vehicle could not be turned on if there are no special requirements. It's guaranteed that background noise is 10 dB (A) lower than a sound pressure level of actual noise in vehicle and experiment results could not be disturbed by other casual noise source.

TIME-FREQUENCY ANALYSIS OF GEAR RATTLE PHENOMENON

On a vehicle idle condition, time-frequency analysis results of acceleration in transverse direction on bearing pedestal of input shaft and in longitudinal direction on the middle part of transmission housing are as shown in Figure 4 and Figure 5 respectively. In Figure 4, vibration acceleration magnitude distributes in frequency range from 500 Hz to 3900 Hz primarily, and maximum value is 100.3 dB. Figure 5 shows that vibration acceleration magnitude distributes in frequency range from 600 Hz to 7000 Hz (especially between 1300 Hz and 3500 Hz), and maximum value is 102.5 dB. Similarly, time-frequency analysis results of noise near the middle part of transmission housing or noise near the driver's ear are presented in Figure 6 and Figure 7 respectively. In Figure 6, sound pressure near middle part of transmission housing is of obvious broadband characteristics. Noise magnitude distributes in frequency range from 450 Hz to 4000 Hz, and maximum value is 60.9 dB(A). In Figure 7, sound pressure near a driver's ear is of obvious broadband characteristics similarly. Noise magnitude focuses in frequency range from 800 Hz to 1500 Hz and maximum value is 34.0 dB(A).

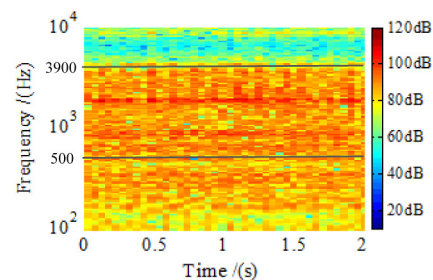


Figure 4. Time-frequency results of acceleration in transverse direction on bearing pedestal of input shaft on idle condition

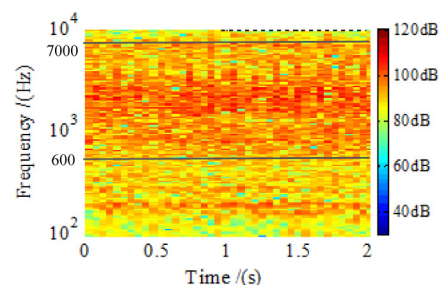


Figure 5. Time-frequency results of acceleration in longitudinal direction on middle part of transmission housing on idle condition

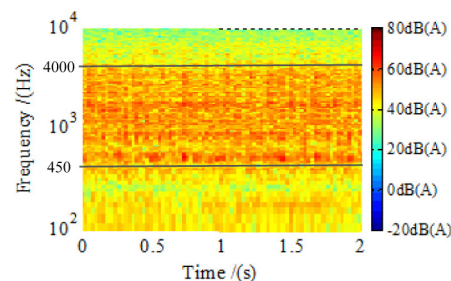


Figure 6. Time-frequency results of noise near middle part of transmission housing on idle condition