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Investigation on Abnormal Gear Rattle Noise in Automated Manual Transmission (AMT) after Gear Upshifting

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ABSTRACT

Customers are getting delighted after receiving best in class vehicle NVH performance. In order to enhance customer NVH comfort, a specific abnormal gear rattle noise phenomenon during product development was investigated. The transmission produces gear rattling noise by impacting gears, oscillating through the gear backlash. Similar noise was observed in one of the prototype vehicle with AMT, immediately after gear upshifting which sustained for some time and then became inaudible. In this case, the noise frequency band was found to be higher than the usual gear rattling frequency band. In this paper, along with the assessment methodology, root causes of this abnormal gear rattle noise will be elaborated.

Keywords: Torsional vibration, Engine knocking

1. INTRODUCTION

In vehicle transmission, sound is generated by excitation in gear teeth meshes and in rolling bearings. Impacts, sliding, rolling, etc. absorb disturbance energy in the elastic structure of system parts and transmit it through the whole structure. Interior surfaces emit a part of this energy into the surroundings in the form of noise (1). Gear rattle noise has little contribution to the overall sound pressure level; however, it significantly impacts the sound quality because it can easily be recognized from the other sounds produced by the automobile. It is for this reason that many researchers have done a great quantity of work in this area to reduce the gear rattle noise. Some of them studied the transmission gear rattle behavior produced by torsional vibrations of the complete driveline (2). Elasis S.C.p.A. used a Virtual Engine Simulator to replace the internal combustion engines in reproducing the mean value of both speed and combustion forces. The experimental results revealed that the gear rattle noise increases with the increase of gearbox input shaft rotational fluctuation (3). The application of a clutch with lower stiffness and a drive shaft with higher stiffness can improve the rotational fluctuation, hence, the gear rattle noise can be reduced significantly (4).

In this paper, all the above probable root causes were investigated namely gear backlash, clutch damper behavior and engine behavior in order to eliminate the abnormal rattle noise phenomenon. A parallel investigation approach was taken where both engine and transmission abnormalities were considered.

2. ABNORMAL GEAR RATTLE NOISE

2.1 Introduction of Vehicle Parameters

Table 1 – Testing vehicle specifications

Name	Parameter values or type
Vehicle kerb weight	825 kg

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Drive mode	Front – engine, Front wheeled drive
Engine type	3 cylinder; 4 stroke
Transmission type	5 – speed; Automated Manual Transmission (AMT)
Fuel type	Gasoline

2.2 Problem Description

During vehicle development phase, gear rattling type of noise was observed from engine cabin while accelerating the vehicle with 10-15% throttle pedal position. The noise was observed inside passenger cabin, immediately after gear upshifting to 2nd, 3rd, 4th and 5th gear, which sustained for some time and then became inaudible in both MT and AMT mode. The noise event which was observed inside passenger cabin is shown in figure 1 where engine speed is plotted w.r.t. time during vehicle running on road in AMT mode.

In order to understand the phenomenon in depth, the vehicle was also driven in WOT condition for ~20 km and this noise was also observed initiating. During further investigation, vehicle was tested on different road gradient and it was found that road gradient plays no role in this noise phenomenon.

2.3 Abnormal Gear Rattle Type of Noise Investigation

Abnormal gear rattle type of noise was investigated with objective data measurement for which different sensors were used. Sensor types and their location in the vehicle are shown in Table 2.

Table 2 – Sensor types and location

No.	Sensor type	Sensor location
1	Single – axis accelerometer	Top surface of transmission housing
2	Microphone	Near top surface of transmission housing
3	Microphone	NFC inside passenger cabin
4	Magnetic pick up sensor for rotational speed measurement	Flywheel
5	Magnetic pick up sensor for rotational speed measurement	Transmission - Input shaft

The objective data was measured, immediately after 3rd gear upshift in AMT mode. Time – frequency analysis results of SPL inside passenger cabin in the frequency band of 500 Hz – 5kHz and 5kHz – 10kHz, SPL near transmission housing top surface and vibration level in Z – direction (refer figure 13) on top surface of the transmission housing are shown in figure 2, figure 3, figure 4 and figure 5 respectively (the magnitude scale of each graph is different).

The SPL was found higher in the frequency band from 1 kHz to 4 kHz inside passenger cabin and additional abnormality was identified at a higher frequency band of 6.3 kHz to 8.7 kHz. It was also found that the magnitude of noise and vibration signature near transmission housing top surface was high between above frequency bands. The noise near transmission housing in the higher frequency band was non-continuous as shown in figure 5, which indicates that some other abnormal noise is also involved from another source apart from gear rattle noise.

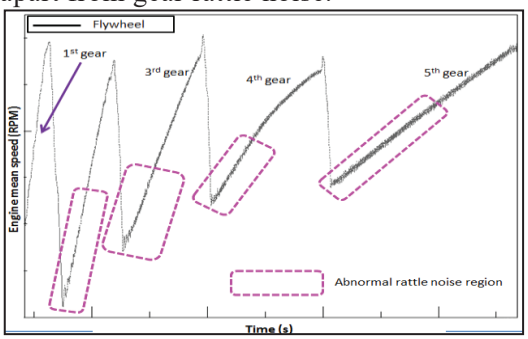

Figure 1– Engine speed w.r.t. time during vehicle running on road in AMT mode

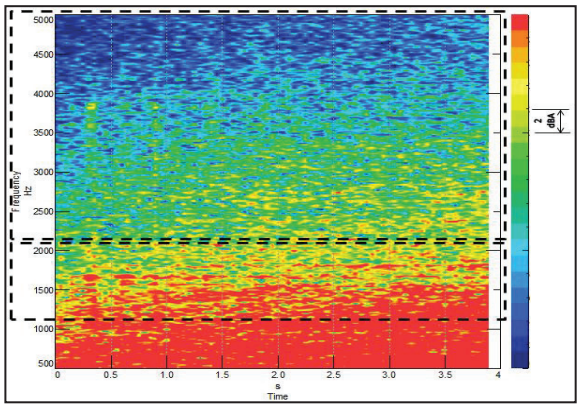

Figure 2 – SPL inside passenger cabin in dBA (500 Hz to 5 kHz)

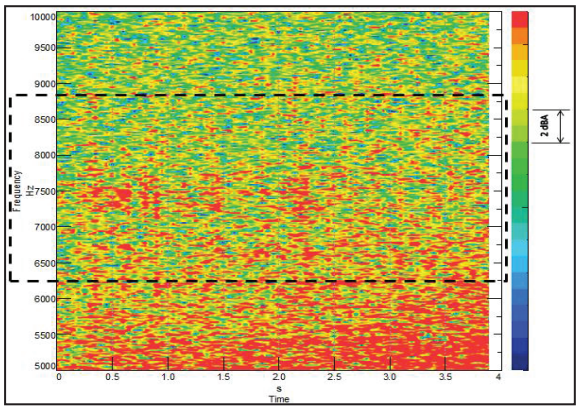

Figure 3 – SPL inside passenger cabin in dBA (5 kHz to 10kHz)

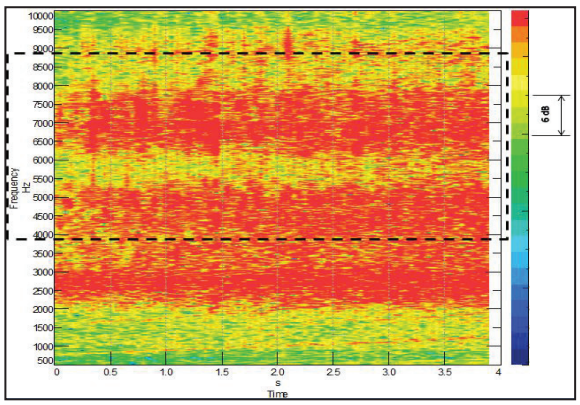

Figure 4 – Vibration on transmission housing top surface in dB

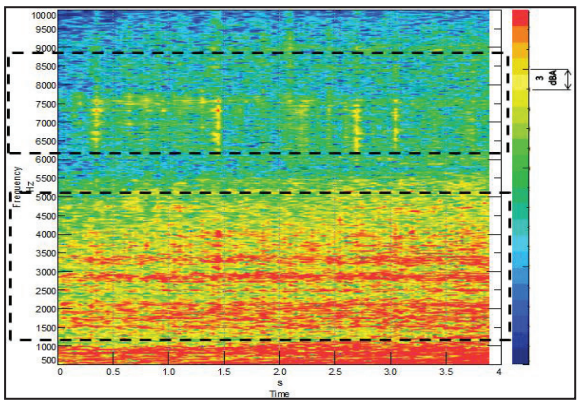

Figure 5 – SPL near transmission housing top surface in dBA

3. INFLUENCE OF MODIFIED GEARS OF TRANSMISSION ON ABNORMAL GEAR RATTLE NOISE

Gear backlash reduction beyond a certain limit will result in improper lubrication during low speed operation. Increment of drag torque or inertia of gears will affect transmission efficiency adversely. Therefore, limits of any subsystem cannot be extended as there is always an undesirable trade-off. Gear backlash design was checked and scope of improvement in final gear backlash was identified among all gear pairs considering manufacturability and assembly constraints. Final gear backlash was reduced by 38%. The objective data was measured, immediately after 3rd gear upshift in AMT mode with optimized final gear pair. Although the overall noise was subjectively reduced, still a different type of rattle noise of higher frequency was clearly audible. Time – frequency analysis results of SPL inside passenger cabin, SPL near transmission housing top surface and vibration on top surface of the transmission housing are shown in Figure 6, Figure 7, Figure 8 and Figure 9 respectively (the magnitude scale of each graph is different)

Subjectively, the gear rattle noise was reduced to substantial level. SPL inside passenger cabin was reduced by ~5 dBA in the frequency band of 1000 Hz - 2000 Hz and ~3 dBA in the frequency band of 2000 Hz - 5000 Hz. The abnormality in gear rattle noise was clearly audible and it was found higher by ~7 dBA in the frequency band of 6 kHz – 9 kHz as compare to its background noise inside passenger cabin as shown in Figure 7. SPL near transmission housing and vibration on top surface of the transmission housing were also found higher in the same frequency band as shown in figure 8 and 9.

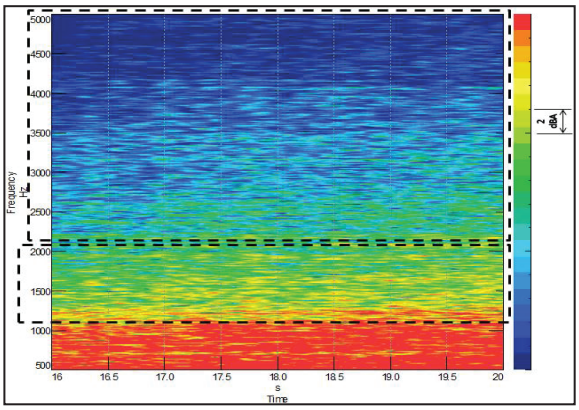

Figure 6 – SPL inside passenger cabin in dBA (500 Hz to 5 kHz)

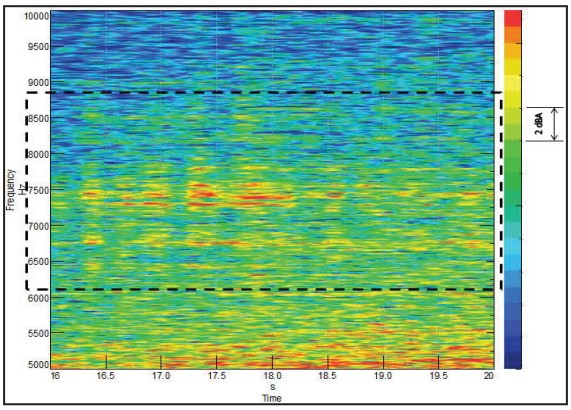

Figure 7 – SPL inside passenger cabin in dBA (5 kHz to 10 kHz)

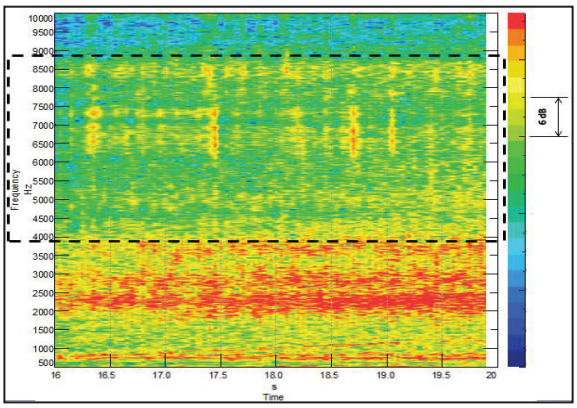

Figure 8 – Vibration on transmission housing top surface in dB

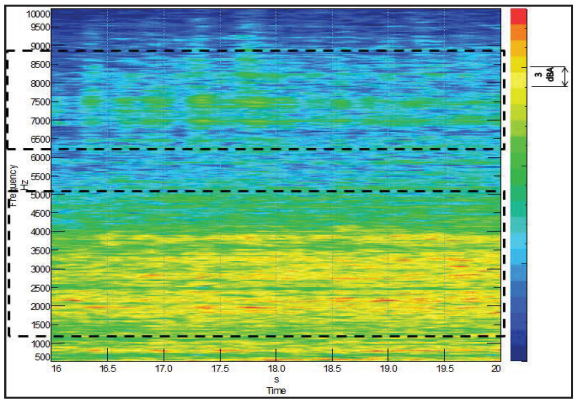

Figure 9 – SPL near transmission housing top surface in dBA

4. Influence of Clutch Damper on Abnormal Gear Rattle Noise

The torsional vibrations produced by the engine are transmitted to the transmission system through clutch damper. There is always lash between the transmission gears, so the torsional vibrations cause rattle noises due to the gear teeth impacting with one another. Flywheel and inputshaft rotational speed was measured w.r.t. time and observations are as follows:-

1. A lag was observed between engine rotational speed and inputshaft rotational speed in each cycle as shown in figure 10.

2. The rotational speed fluctuation of inputshaft was found higher by ~30 % than that of engine speed fluctuation and behavior was abnormal as shown in figure 11. Preferably, inputshaft speed fluctuations must be equal or less than engine speed fluctuations.

It was hypothesized that the above behavior was inducing excitations in free gears and causing drive rattle.

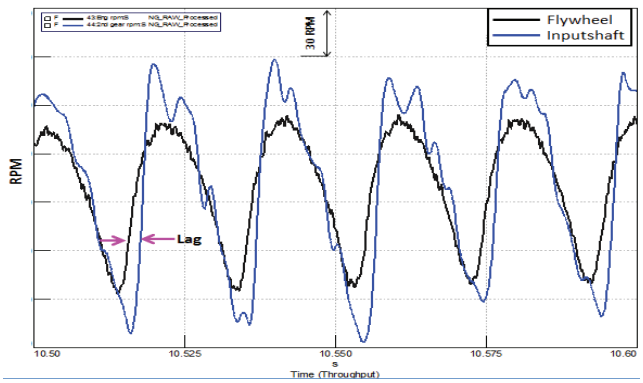

Figure 10 – Rotational speed of flywheel and inputshaft in RPM; with standard clutch in 3rd gear; AMT mode

One of the most important tasks for the clutch is to reduce the torsional vibration of the flywheel. With the popularity and development of high-powered engines, higher demand is required for clutch to reduce the flywheel torsional vibration. Among the parameters to reduce the torsional vibration, the spring stiffness and hysteretic damping of clutch are the most important factors. Based on the parametric sensitivity analysis, some control strategies, including increase of the clutch damping hysteresis and decrease of clutch spring stiffness (5). This led us to investigate the clutch damper further and upon measurement, it was observed that the clutch damper hysteresis was manufactured lower than what it was designed for. The speed fluctuations of inputshaft speed were reduced to slightly less than engine speed fluctuations as shown in figure 12.

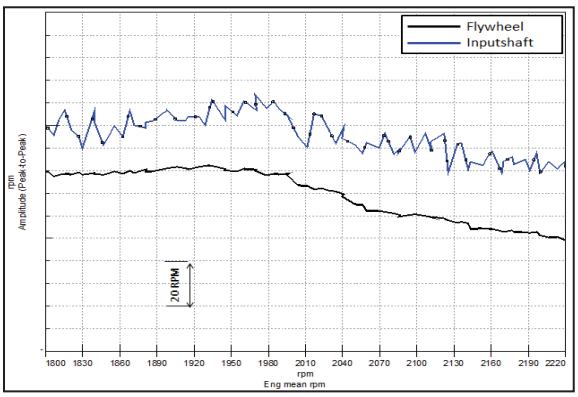

Figure 11 – With standard clutch; 1.5th order - Torsional fluctuations (RPM) 3rd gear; AMT mode

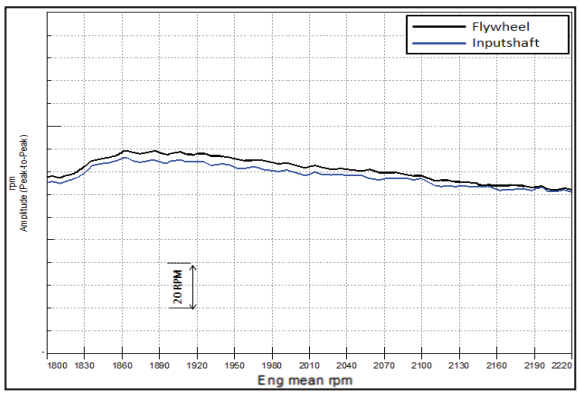

Figure 12 – With modified clutch; 1.5th order - Torsional fluctuations (RPM) 3rd gear; AMT mode

5. ROOT CAUSE ANALYSIS OF ABNORMALITY IN GEAR RATTLE NOISE

5.1 Time – lag Analysis

With modified (improved) clutch and gears, the gear rattle noise was significantly reduced. However, the abnormality in gear rattle noise was still perceivable. The vibration signal was measured on engine cylinder 1 head and top surface of transmission housing with the help of accelerometer fixed on positions as shown in figure 13. It was natural that the vibration level of engine cylinder 1 head top surface and transmission housing top surface will not be same due to different dynamic behavior of components inside respective systems.

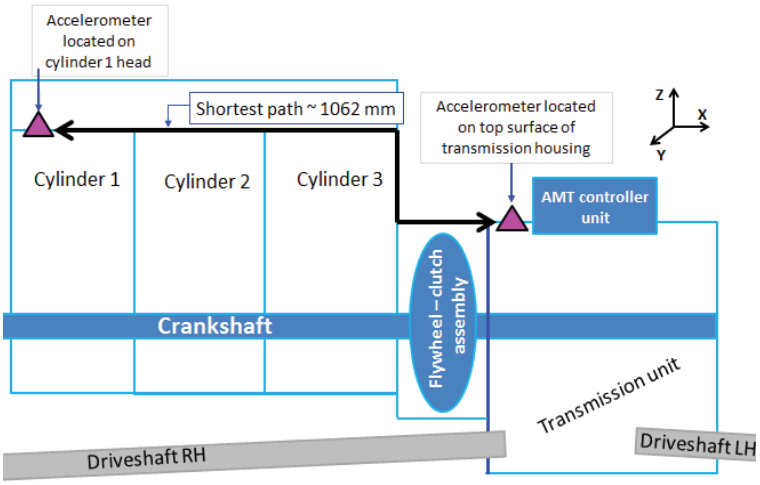

Figure 13 – Acceleration sensor position on cylinder 1 head top surface and transmission housing top surface

Mittal, V., Revier, B., and Heywood determined knock intensities for each cycle by using Fast Fourier transforms (FFT) and bandpass filtering techniques. Primarily two ranges of frequencies can be excited during engine knocking phenomenon: the lower frequency is just above 6 kHz and corresponds to the first circumferential frequency of the combustion chamber. The microphone data

shows that the audible knock signal has the same 6 kHz peak. The second range of peaks in the 15-22 kHz frequency band (6). The wave signal of 7362 Hz – 7362.5 Hz was filtered and plotted w.r.t. time as shown in figure 14. The data was acquired in every 39.0625 µs. The magnitude of signal is rising w.r.t. time and the signal from accelerometer near cylinder 1 head was found ahead by ~ 191.5999 µs than transmission housing. This time is sufficient to travel ~1074 mm from accelerometer located near cylinder 1 head to transmission housing through metallic medium. This indicates that this wave was originated from engine and propagated towards transmission.

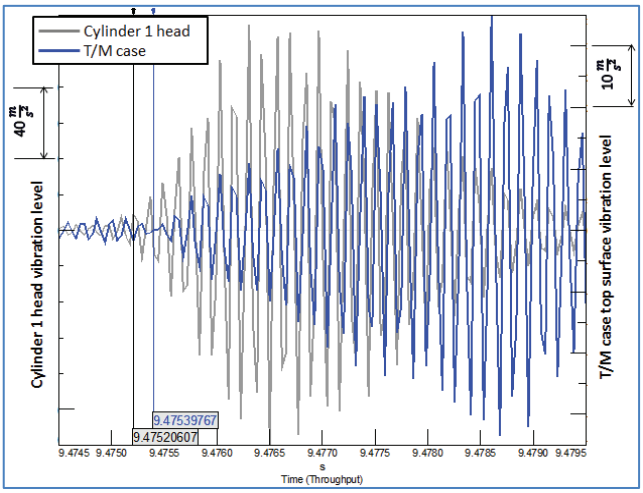

Figure 14 – Vibration signal; Filtered: 7362 Hz – 7362.5 Hz frequency w.r.t. time; 3rd gear; AMT mode

5.2 Engine Knocking Phenomenon

Vibration level through accelerometer near engine cylinder 1 head is plotted w.r.t. engine combustion cycles and time as shown in figure 15. The vibrations were found to be cyclic in nature. Further investigation of engine was done by instrumenting a pressure sensor in place of spark plug which can provide spark as well as can measure cylinder pressure simultaneously. The main reason of occurrence of these vibrations was found to be uncontrolled combustion inside all three cylinders.

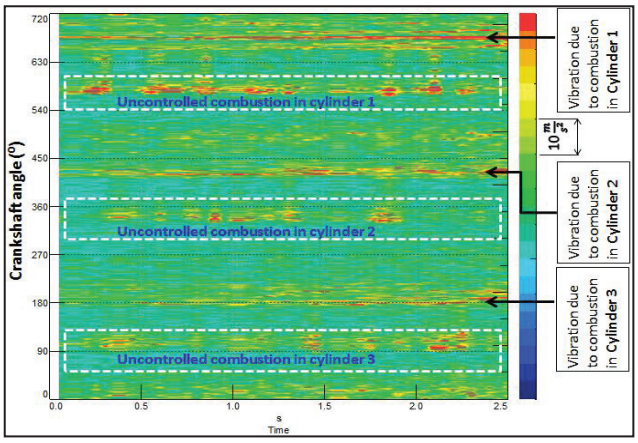

Figure 15 – Vibration on cylinder 1 head top surface in m/s^2; 3rd gear; AMT mode

6. Influence of Modified Gears, Clutch and Engine Calibration on Abnormal Type of Gear Rattle Noise

Retarded spark supports to decrease the engine knock because comparatively lower maximum engine pressures are produced. The maximum pressure occurs late in the cycle during the power stroke and is not as high as that of the normal case. The engine knocking noise and shock vibrations were significantly reduced after engine calibration optimization. Vibration level through accelerometer near cylinder 1 head is plotted w.r.t. engine combustion cycles and time as shown in figure 16.

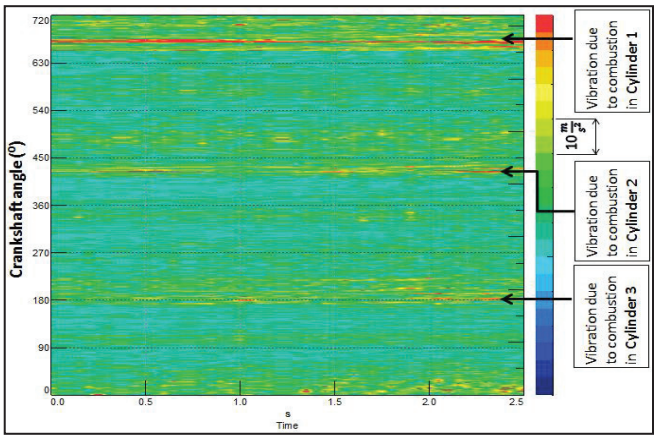

Figure 16 – With modified engine calibration; Vibration on cylinder 1 head top surface in m/s^2; 3rd gear; AMT mode

With modified condition (modified clutch, gears and engine calibration), inputshaft speed was found completely synchronized with the engine speed as shown in Figure 17.

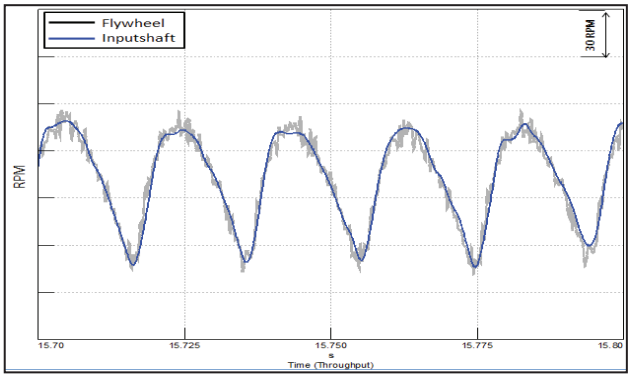

Figure 17 – Rotational speed of flywheel and inputshaft in RPM; with modified gears, clutch and engine calibration in 3rd gear in WOT condition; AMT mode

Time – frequency analysis results of noise inside passenger cabin and vibration on top surface of transmission housing are shown in figure 18, figure 19, figure 20 and figure 21 respectively (the magnitude scale of each graph is different). Improvement can be easily seen as compare to standard condition.

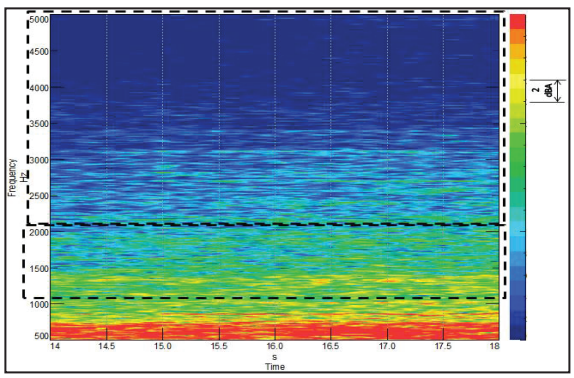

Figure 18 – With modified condition; SPL inside passenger cabin in dBA (500 Hz to 5 kHz)

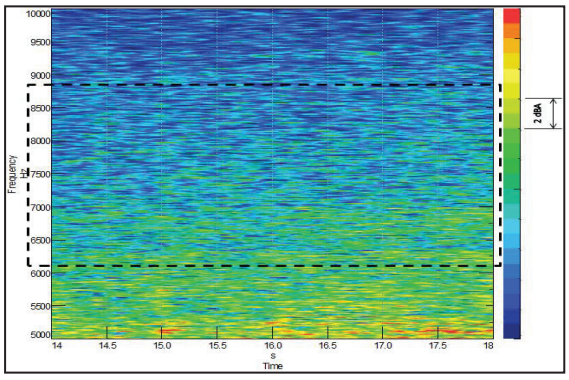

Figure 19 – With modified condition; SPL inside passenger cabin in dBA (5 kHz to 10 kHz)

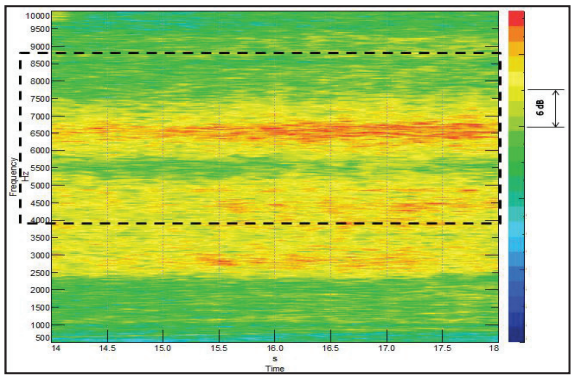

Figure 20 – With modified condition; Vibration on transmission housing top surface in dB

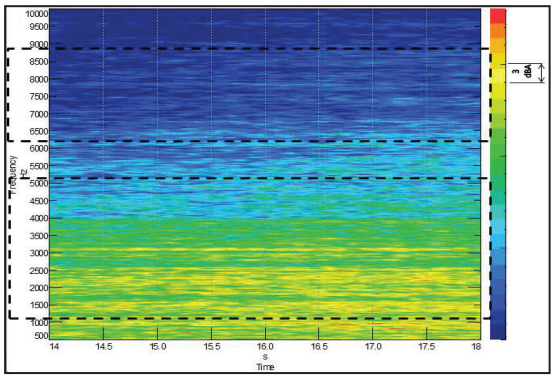

Figure 21 – With modified condition; SPL near transmission housing top surface in dBA

7. SUMMARY/CONCLUSIONS

Experimental approach is established for understanding abnormal gear rattle noise and torsional vibration behavior. Gear rattle noise along with engine knocking noise was studied and eliminated successfully.

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Abbreviations / Units

MT	Manual transmission	WOT	Wide open throttle
v/s	versus	TM	Transmission
RPM	Rotation per minute	NFC	Noise front row center
w.r.t.	with respect to		
SPL	Sound Pressure level		
dBA	Decibel (A - weighted)		