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# Experimental Investigation into the Transient Response of an Automotive Powertrain with an Automatic Transmission during Gear Shifts and Torque Reversals

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## KEYWORDS

Powertrain dynamics, driveline dynamics, gear shift quality, clunk, transient response, automotive test rigs

## ABSTRACT

This paper presents an experimental investigation into the transient torsional response of a powertrain fitted with an automatic transmission under various operating conditions. The powertrain test facility is briefly described along with the development of a wireless torque transducer. A number of tests are performed including engine torque tip-in and 1-2 and 2-3 automatic transmission gearshifts. The transient output torque of the transmission is measured and analysed. We discuss some quantifiers for the system response during torque ramps and torque and inertia phases of gear shifts. Clearance induced impact (clunk) events due to torque reversals are captured in acceleration measurements during engine torque tip-in from engine idle and examined in the time and frequency domain.

## INTRODUCTION

Test rigs for automotive powertrains provide controlled conditions for the study of dynamic response. Measurements of torque, motion, hydraulic pressures and the like provide both an understanding of the dynamics at work and data for comparison with analytical and numerical studies. For system level problems we need the whole powertrain, thereby capturing interactions between engine, transmission and driveline. In this paper we present some test results and updates on our powertrain test facility, including some of the challenges faced in development. The underlying motivation for the research is to evaluate the gearshift quality of a powertrain under various operating conditions and driver demands (e.g. heavy load, tip-in and kick-down).

A class of problems for the powertrain is system transient response under varying mean engine torque, engagement or disengagement of friction elements and/or system parametric variation (gear shifts). Non-linear elements bring added complexity, with clearances, friction non-linearities, multistage stiffness elements (clutch-damper) and fluid couplings (torque converter) playing a role in dynamics. Often several of these non-linear elements are interacting in the system simultaneously; such as driveline clunk [1] under engine torque tip-in/out where the powertrain includes a clutch damper and multiple clearances. The multistage stiffness shapes the response before reaching the clearance element, i.e. bevel pinion and ring gear, hence influencing the nature of the impact.

Works have been published on these types of problems where researchers have developed test rigs to obtain data. Some examples are automatic transmission gear shifting [2-3], driveline transient vibration (shuffle) [4], clunk induced by shuffle [1, 5-6] and park disengagement thump [7]. Here we discuss three papers general to the available research. Testing [4] was done on-vehicle to measure engine torque and shuffle characteristics. They determined engine inertia and an estimation of drivetrain friction torque. Instrumentation provided engine pressure, engine oil temperature, overall equivalent ratio and crankshaft rotation. They raised the vehicle to investigate steady state friction losses without road/tire contact. Couderc et al. [8] used a Hooke's joint to simulate engine harmonics, they compared their manual transmission driveline test rig data to model/simulation for natural frequencies and some transient responses. The natural frequencies were found experimentally by running the test rig up slowly within a speed range. The arrangement of the rig given in [5] is characteristic to those investigating shuffle and clunk; a powertrain, grounded at the tires, was preloaded at the engine with 100Nm of torque and released. Driveshaft torque reversals (passing through the backlash) correlated with simulations and the impact (clunk) was evident.

Within this paper we briefly discuss our test rig and some instrumentation. The results are presented for three experiments with transient responses to engine torque tip-in from idle and in 1-2 and 2-3 automatic transmission gearshifts. The data includes engine speed, driveshaft speed and torque. Acceleration measurements at the rear axle housing recorded the clunk event on engine torque tip-in from idle.

## POWERTRAIN TEST FACILITY

The test facility (Figure 1) has been developed for experimental investigation of the dynamics of vehicle powertrains fitted with various types of transmissions [9]. The facility's major components include a 6-cylinder spark-ignition engine, 4-speed automatic transmission, driveline and a system providing equivalent vehicle inertia and load. This subsystem has 4 train wheels providing a total of 75kgm$^2$ of inertia at the tire through rolling/sliding contact. A dynamometer provides variable load through coupling to the flywheel shaft. The facility can be used for: experimental validation of theoretical predictions of the transient characteristics of automatic transmissions during gear changes; implementation of closed loop control of gear shifts; and in particular, experimental investigations of torsional vibration of a complete powertrain caused by various nonlinearities and drive conditions. Analysis involves finding free, steady state and transient responses of torsional systems through various linear and nonlinear approaches (harmonic balance, Runge-Kutta, shooting methods).

For data acquisition the engine and transmission control signals are tapped. Accelerometers are fixed on the transmission and rear axle housings. They are mounted on the drive and axle shafts and wheel rims for free vibration tests only. Torque is measured via the torque telemetry system described next. Data is recorded and post processed with Lab View. The measurements obtained from the facility include: engine, transmission output (driveshaft) and half shaft torque and angular velocity; housing accelerations; sump temperature; and transmission solenoid signals and throttle position.

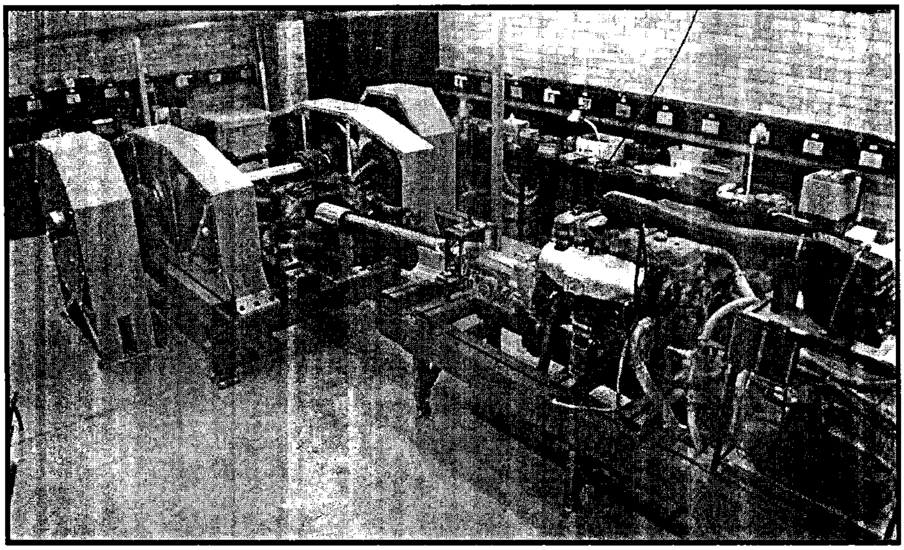

Fig. 1. Powertrain test facility

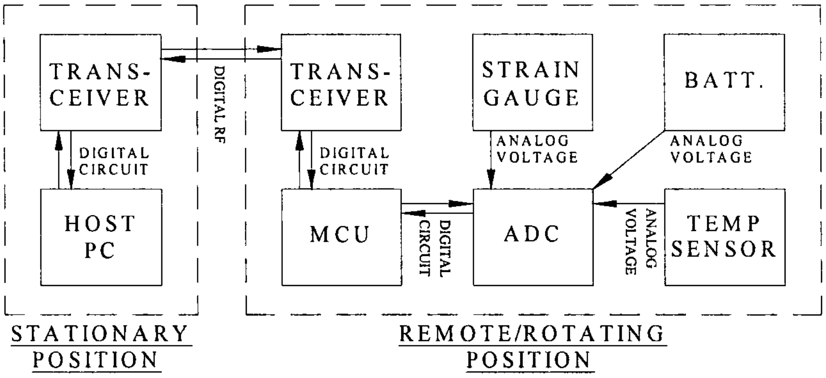

Fig. 2. Torque telemetry measurement system

## DEVELOPMENT OF WIRELESS TORQUE TRANSDUCER

The wireless torque measurement system is used to record the dynamic torque at various points on the powertrain. Strain gauges are attached to the surface of components that rotate and transfer power.

### Torque Telemetry System

A system overview is given by Figure 2. The micro-controller unit (MCU) is programmed to take readings through its internal analogue to digital converter (ADC) upon command from the host computer. The commands and data are transmitted via a pair of TR3100 transceivers. The host PC is used for controlling the remote circuit board functions. It contains an analogue section, a micro-controller, a radio transceiver, batteries and voltage regulators. The PCB takes commands from the PC. The features of the major sections of the torque measurement system PCB are:

- Analogue section with instrumentation amplifier and filter for torque channel, on-board shunt calibration, PCB temperature measurement via a temperature sensing IC and battery voltage sensing.

- Micro-controller: Atmel Atmega8535, with an MCU system clock speed of 7.3728 MHz, USART baud rate of 115.2 kbps and 10 bit ADC.
- Radio transceiver: RFM TR3100, with transmitting protocol, Amplitude Shift Keyed (ASK) and transmitting frequency of 433.92 MHz.
- Three 3 Volts batteries were used and voltage regulators were used for each of the above major components.

The desired ADC sample rate is approximately 6 kHz. However due to the bandwidth limit of the RF link, the sample rate has been lowered to 4.43 kHz and every pair of samples is averaged to give a transmitted sample rate of 2.21 kHz.

### Micro-Controller Software

The software was written in the C programming language using CodeVision AVR. The CodeVision AVR program and compiler allows the software to be loaded directly onto the micro-controller unit through a serial port connection. The software includes a) Command functions within the command structure; b) Encoding / Decoding; c) Control of MCU features using the universal synchronous and asynchronous receiver transmitter (USART) that controls the data being sent and received by the MCU; and d) Control of the ADC analogue sub-system power and shunt calibration.

### Calibration of Torque Channel

After setting the gain of the instrumentation amplifier to suit the required torque measurement range, an end-to-end calibration is done to calibrate the torque measurement system. This is with the powertrain stationary and applying a known static torque to the strain gauged powertrain component. The resulting change in torque reading is then noted at the PC.

### Effect of Rotating Speed

The rotating PCB has been spin tested by mounting it on the shaft of an electric motor and driving the motor up to 6000 rpm. When this test was first performed it was noticed that the batteries moved inside their battery holders and contact was lost. An additional battery clamping clip on each battery was designed and installed. The test was repeated and no mechanical or electrical problems were observed.

### Lost Data Packets

There are still minor issues with the torque sensor to be resolved. The data flow is periodically interrupted by a software handshaking issue and occasionally a data packet will be corrupted by RF noise. These challenges should be overcome in the new version of the sensor that is currently being developed.

## EXPERIMENTAL RESULTS

This section presents the results obtained from several experiments performed with the powertrain facility. These are characteristic of those that will be used for more thorough studies. Here we point out some of the key features and note comparisons to prior simulation studies/experiments.

## Experiment I: Transient Response of the Powertrain under Tip-in Conditions

This experiment is to capture the transient output torque of the automatic transmission (driveshaft torque) from engine torque tip-in from idle to 50% throttle position for 1s and then backed-out to 20%. The measured torque (Figure 3) is included with engine and driveshaft speed and throttle. The driveshaft torque ramps up due to the throttle increase and we define three quantifiers for this response; the lag between (throttle) input and a inertia element, $\tau_d \approx 0.29\text{s}$, here $d$ denotes driveshaft; the average slope of the torque ramp, $\gamma = dT_d/dt \approx 109\text{Nm/s}$, across the section $t \in \{t_1 + \varepsilon : t : t_2 - \varepsilon\}$ with $\varepsilon = 0.15(t_2 - t_1)$; and the change in mean torque, $\Delta T_d = T_d(t_2) - T_d(t_1) \approx 38\text{Nm}$.

We would expect to see response at the lowest global torsional mode (shuffle), at about 1-3Hz. The absence is likely as the mode is highly damped from the characteristics unlocked torque converter; which we should add is in a transient state.

What we did not to expect to see in this test was the instability (around 13Hz) develop following the rate of change of throttle flattening to zero (just before $t = 76.4\text{s}$). The instability grows in the driveshaft torque after the time-lag and some time after the throttle back-out and gear shift it fades away. The missing data is due to the lost data packets, at an inopportune time. The frequency is found to be constant over the transient period and therefore it may relate to one of the natural frequencies of the powertrain system. We have seen this instability in the torque develop in several tests and will look into the causes with review and simulation studies.

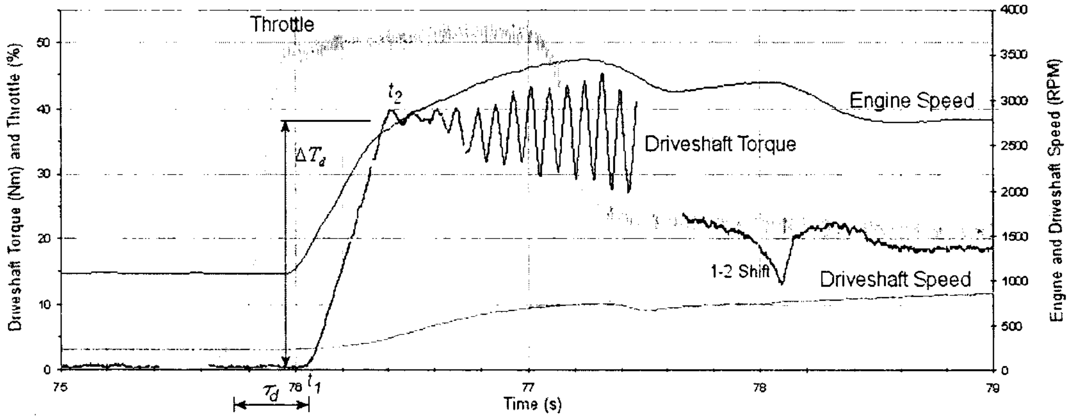

Fig. 3. Driveshaft torque and speed, and engine speed and throttle setting as measured for engine torque tip-in

## Experiment II: Transient Responses of the Powertrain during Gear Shifts

For this experiment, a light load was applied to the powertrain. Throttle was tipped in from an idle setting to 38% and held steady. The flywheels are accelerated gradually from idle speed through 1-2 and 2-3 gearshifts. The tip-in (Figure 4a at $t \approx 16.5$s is quantified by time lag, $\tau_d \approx 0.25$s, mean torque rise, $\Delta T_d \approx 37.5$Nm and slope $\gamma \approx 111$Nm/s. Again the torque fluctuations after tip-in are at around 13Hz and response in the shuffle mode is not evident. This result shows less instability than Experiment II. The steadying of the torque fluctuation coincides with the start of the 1-2 gearshift (at $t \approx 18.1$s ).

Figure 4b shows the time history of transmission solenoid states; these solenoids control the hydraulic system. Omitting the finer points in this brief communication, we note the 1-2 shift takes place when the pressure increases on the brake band, holding rear sun gear and overrunning the one-way clutch (see [10] for details). This gives two phases; a torque phase, where the output torque drops and the transmission speed ratio is constant and an inertia phase where the both torque and speed ratio change. In Figure 4b, the VPS solenoid state shows that shift starts at 18.1s. It ends when a brake band pressure is large enough to hold a planetary gear element (rear sun). Figure 5 shows the 1-2 shift has durations for torque hole as $\tau_h \approx 0.1$s and inertia phase as $\tau_{ip} \approx 0.35$s. Using the VPS signal and the phase transition point the torque phase is determined as $\tau_{tp} \approx 0.7$s. The end of the shift is characterised by the 'step' down in torque at $t \approx 19.15$s from torque overshoot ($\Delta T_{ip} \approx 6$Nm) in the inertia phase. The 'step' is due to the abrupt nature of the brake band engagement. These dynamics are similar to those shown in simulations [10]. We also define on the figure; torque drop, across the torque phase, $\Delta T_{tp} \approx 7.5$Nm and change in mean torque, $\Delta T_m \approx 2$Nm.

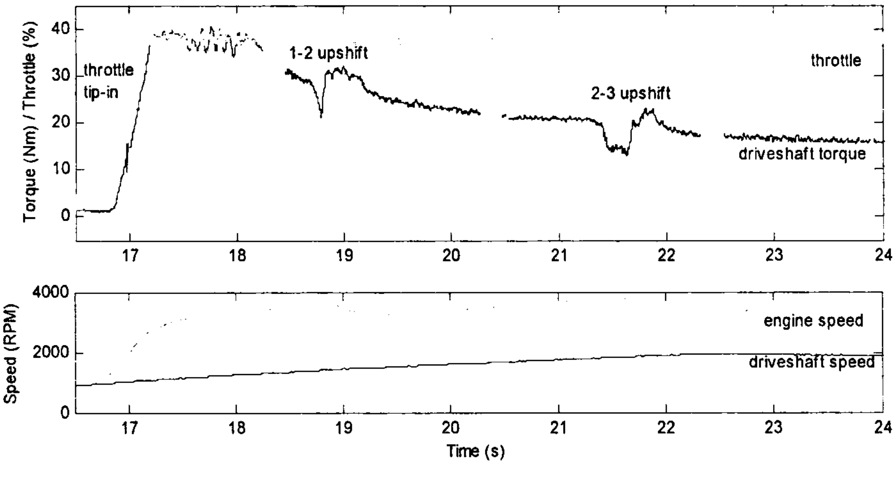

Fig. 4a. Driveshaft torque and speed, and engine speed and throttle setting as measured for automatic transmission 1-2 and 2-3 gearshifts

For the 2-3 gearshift, in Figure 4a, the solenoid states show that the shift duration is 1.3 seconds with a torque phase of 0.9 seconds and an inertia phase of 0.4 seconds. Quantifiers similar to that for 1-2 shift can be applied to this transient. The paper [11] provides details on the 2-3 shift mechanism and some qualitatively comparable simulations which were performed before the test rig was completed. Future work should include efforts to match experimental results to new simulations.

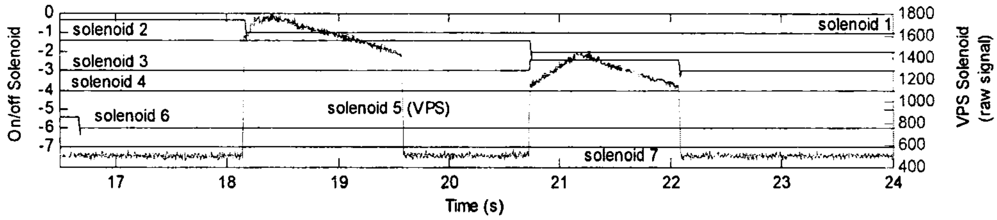

Fig. 4b. Solenoid states for automatic transmission 1-2 and 2-3 gearshifts

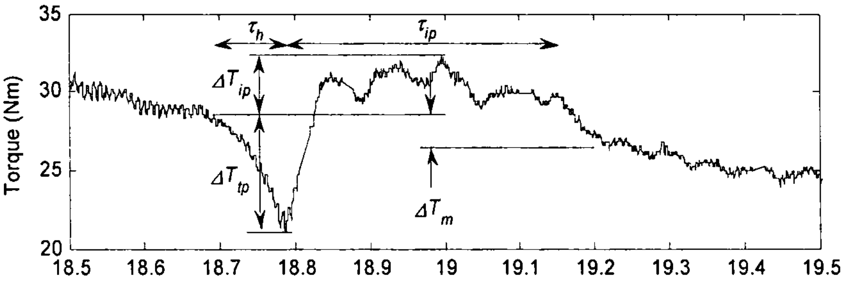

Fig. 5. Driveshaft torque as measured in a 1-2 gearshift

## Experiment III: Clunk Event Induced by Transient Response to Engine Tip-in

Clunk is problematic for OEMs, particularly in SUVs and light trucks. There are manufacturing clearances, or lashes, in mechanical couplings and geared contacts. When the transmitted torque reverses its direction, either through mean change and/or oscillations, the contacting elements pass into and out of their clearance. The impact may take place on the side of entry or after passing right through the clearance.

We have previously correlated experiment and simulation for this dynamics in a non-running condition (driveline free vibration). The powertrain test rig now allows experiments to induce and record clunk and driving inputs in the running condition. Measurements can be taken with accelerometers in various locations (such as the pinion-nose position and along the various paths) and with microphones.

A typical result for the measured clunk response is shown in Figure 6. The driving condition is a tip-in from idle in first gear (with unlocked converter). Before ramping up the driveshaft torque featured a small dip into negative, commencing at $t \approx 0.3$s for about 100ms. Lag from throttle input, $\tau_d \approx 0.25\text{s}$, (before the dip) was similar to Experiments I and II. On the ramp up the torque crossed from negative to positive and this would have induced the clunk. The major impact is at around 0.8s with possibly minor impacts beforehand; these may be at multiple locations due to many clearances (at driveshaft joints, rear axle bevel and differential gears, and transmission gears) and the dynamics may include interactions between nonlinearities. The torque and acceleration are measured respectively at transmission and rear axle sides of the driveline and we need to consider the path in interpretation of the data. Impact events will be at different times and the response to each event at the measurement locations

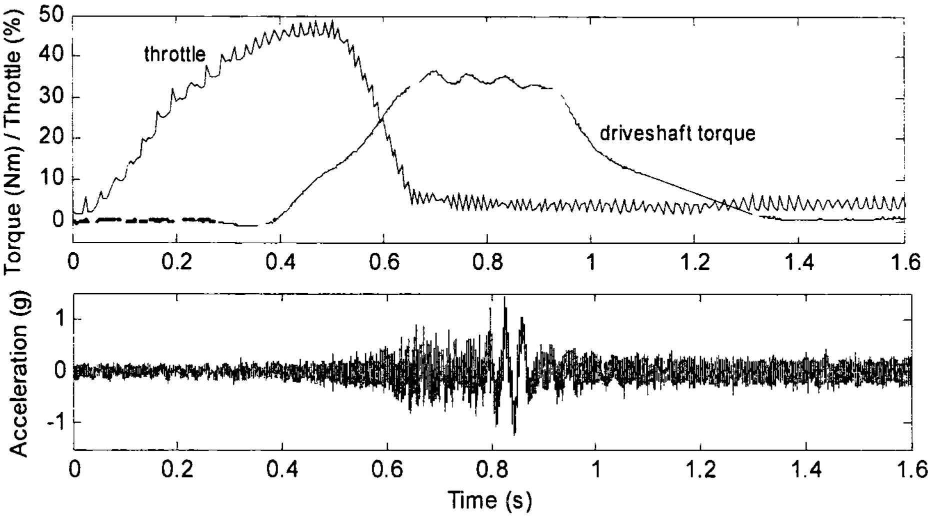

Fig. 6. Throttle, Driveshaft Torque and Rear Axle Housing Vertical Acceleration as Measured for a Typical Clunk Event

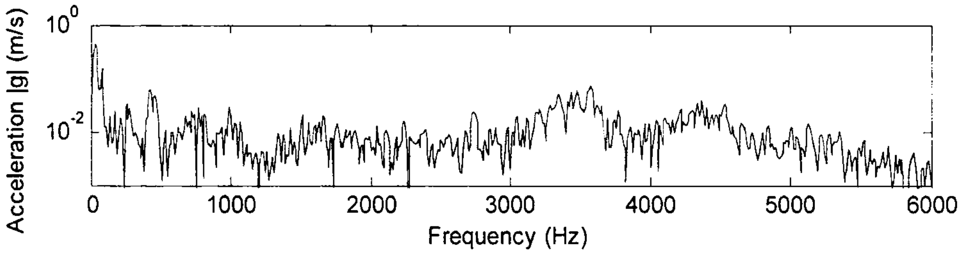

Fig. 7. Short-time frequency spectrum of measured acceleration for a typical clunk event (centred at $t_c = 0.8$s, short time period $\tau = 0.1s$)

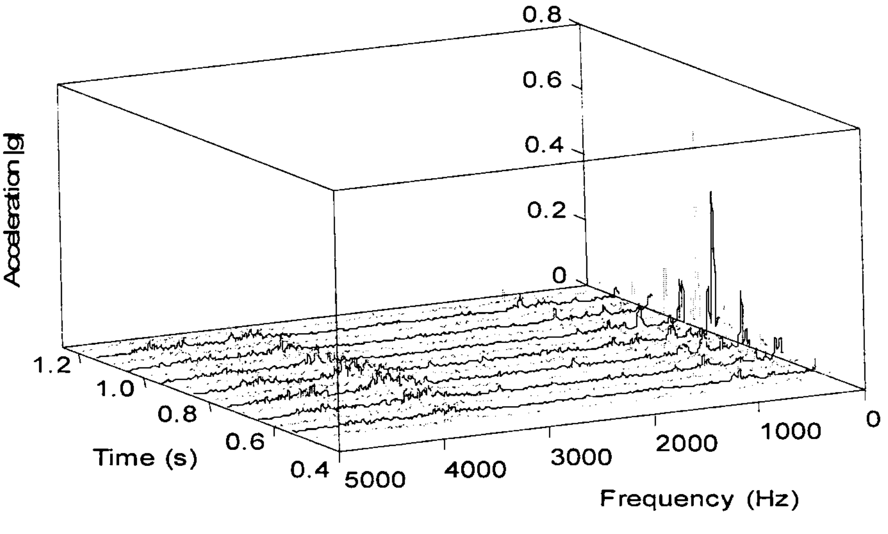

Fig. 8. Waterfall plot of measured acceleration for a typical clunk event (short time period $\tau = 0.1s$)

will have a time lag while the impulse propagates through the system. This can leave quite a complex signal with more than just a single obvious clunk. This complexity of multiple impacts has been explored in [12] for a large map of simulated clunk events, they also introduce various metrics for quantifying the magnitude of the impact(s).

Figure 7 shows the short time frequency spectra for a segment of the clunk event, centred at $t_c = 0.8\mathrm{s}$ with short time period $\tau = 0.1\mathrm{s}$. This is one section from the waterfall plot of Figure 8. Each short time vector was Hanning windowed and zero padded. From around 0.6s to 0.95s the frequency content has highest peaks around 34, 250, 437, 1000, 3500 and 4500 Hz. We would like to see if further tests give similar results and make comparisons with experimental modal analysis of the rear axle structure.

## CONCLUSIONS

This paper introduces experimental investigations for the transient response of a powertrain due to engine torque tip-in and automatic transmission gearshifts. We describe our powertrain test facility and wireless torque measurement system. Three experiments are performed with specified operating conditions. The first shows under throttle tip-in a significant or even unstable torsional vibration may exist in the transmission output shaft and driveshaft (as measured torque). The second shows a take-off followed by 1-2 and 2-3 gearshifts with obvious torque and inertia phases and transient torque oscillations during and after the shift. The third shows a typical clunk event as measured acceleration on the rear axle housing and we discuss the possibility of the clunk signature including response to multiple impact events at multiple clearances. A waterfall plot shows the rise and fall of various peaks in the frequency spectra as you move through the time history.

There are still some challenges in the development of the test rig, such as building a control system for the throttle, resolving communication issues of lost data packets in the torque telemetry system and improving and verifying the synchronization of the various measurements. The facility will allow exploration of many problems rich in dynamics that plague powertrain systems through experiment and analysis.

## ACKNOWLEDGEMENTS

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