

Aggressive Torque Converter Clutch Slip Control and Driveline Torsional Velocity Measurements

Paul Otanez, Farzad Samie, Chunhao Joseph Lee and Chi-Kuan Kao

General Motors Research & Development

Copyright © 2008 GM Global Technology Operations, Inc. Published by SAE International with permission.

ABSTRACT

In automatic transmissions, an open torque converter transmits torque from the engine to the transmission using fluid coupling. Although torque converters are ideal launch devices for automatic transmissions, they are inefficient in steady-state operations. An electronically controlled capacity clutch (ECCC) is implemented to control the slip between the pump and turbine of the torque converter, thereby increasing its energy transfer efficiency and increasing vehicle fuel economy. Even though reducing torque converter slip minimizes losses due to fluid coupling, it also decreases the damping provided by a slipping torque converter and as a result increases the sensitivity of the driveline to engine excitations. This investigation uses driveline torsional velocity response measurements to evaluate the effects of using slip feedback closed-loop control with a very aggressive torque converter ECCC slip schedule in automatic transmissions. Experimental results for a General Motors Sport Utility Vehicle equipped with a 6-speed Rear-Wheel-Drive automatic transmission with and without all-wheel-drive, and different torque converter isolator configurations are presented. The effects of the very aggressive ECCC slip strategy on vehicle drivability are also discussed.

INTRODUCTION

Improved fuel economy can be achieved by optimizing the design of the transmission. Increasing the transmission ratio spread and increasing the number of gear ratios are two ways that the efficiency of the drivetrain can be improved. However, minimizing the energy loss from the slip of the pump and turbine in the torque converter has the potential to provide a very significant improvement in fuel economy. Although reducing (or under some conditions eliminating) torque converter slip would improve fuel economy, it can compromise driveability by increasing the sensitivity of the drivetrain to engine disturbances.

The torque converter is an important part of a transmission since it is used during vehicle launch and also provides torque multiplication, smooth ratio

changing on acceleration, and driveline torsional vibration damping. However, the difference in slip between the torque converter's pump and turbine reduces the energy transfer efficiency of the device. A locking clutch, often referred to as a torque converter clutch (TCC), is generally used along with an isolator to mechanically lock up the converter to reduce losses at higher vehicle speed conditions [1]. At low vehicle speeds and in lower gears, the TCC is generally not applied because a locked driveline would pose driveability concerns in terms of objectionable driveline vibrations [2]. However, slipping the TCC at small slip values has been successfully employed in order to tradeoff fuel economy and vehicle driveability [3, 4]. In the literature, actively controlling the slip in the torque converter is known as electronically controlled capacity clutch or ECCC [3].

Although automobile manufacturers would like to improve vehicle fuel economy by applying ECCC as often and as aggressively as possible, there are several repercussions that must be considered. The more frequent application of ECCC requires that the TCC must be capable of a greater number of engagements at higher energies than in the past. As a consequence, the limited heat capacity of conventional single friction plate TCCs has led to the development of multiple friction plate TCCs which provide better heat capacity due to the larger clutch surface area [4]. Noise, vibrations, and harshness (NVH) due to drivetrain torsional vibrations compromise driveability and therefore constrain ECCC application. To mitigate NVH effects extra attention must be paid to the isolator design and the TCC control system [5]. Although any controller design technique is applicable, Proportional-Integral-Derivative control in which TCC slip is the feedback variable is a commonly used technique.

Finding an optimal compromise between the necessary slip for vibration decoupling and minimizing slip for fuel economy is an area of active research. This investigation analyzes experimental results that evaluate the effects of different levels of torque converter slip on the driveline torsional vibrations. The vibrational response of a driveline is presented and analyzed for

two types of torque converters and when the vehicle is in all wheel drive or rear wheel drive. An aggressive ECCC strategy is then tested in order to demonstrate the ramifications of minimizing TCC slip for fuel economy on driveability.

This paper is organized as follows: 1) the implementation of feedback closed-loop torque converter slip control is summarized, 2) vehicle driveline torsional measurements collected on a chassis dynamometer are presented, 3) the application of an aggressive ECCC slip schedule using driveline torsional measurements is evaluated, and 4) a summary of the findings as well as conclusions is presented. The diagrams and figures referenced in this investigation are found in the Appendix.

FEEDBACK CLOSED LOOP CONTROL

In an automatic transmission, both the torque converter and the converter clutch can carry torque from the engine. This feature provides an advantage compared to normal hydraulic clutches inside the transmission for gear shifts. When the TCC is released, the engine torque is transmitted directly through the torque converter, which is a natural damping device due to its hydro-dynamic characteristics. The engine torque is mainly transmitted through the clutch when the TCC is engaged and the slip between the pump and the turbine of the torque converter is actively controlled. However, fluid coupling in the torque converter damps engine pulses of medium to high frequency. The torque converter's isolator (spring damper) mitigates engine disturbances at high frequency when the TCC is locked and the driveline is fully connected.

A system level diagram of the ECCC control algorithm is shown in Figure 1. The algorithm receives the following information from the engine controller: engine speed, estimated engine torque, and throttle opening. The following information is also sent by the transmission controller: transmission turbine (input) speed, line pressure, and transmission gear states (including gear shifts). The output from the ECCC algorithm is the pressure command sent to the TCC required to maintain a desired torque converter slip.

A combination of feedforward pressure control and slip speed feedback compensation is used when the TCC actively controls the slip at the clutch. The feedforward pressure is designed to be proportional to the estimated engine torque. This is because the majority of the engine torque is transmitted through the converter clutch when slip control is active. An advantage of making feedforward pressure a function of the estimated engine torque is that it can compensate for the hydraulic system delay because the engine controller uses several variables to predict engine torque. The feedforward pressure, P_{ff} , is proportional to the estimated engine torque, T_{eng} ,

$$P_{ff} = K_{eng} T_{eng},$$

where K_{eng} is a function of the throttle opening. Feedback compensation is calculated based on the desired slip level and the slip measurement. The TCC slip feedback loop can be synthesized using any control theory design technique. For simplicity, a classical proportional and integral controller is employed in this investigation.

Similar to the current production algorithms used in General Motors (GM) transmissions [6], the ECCC algorithm has three distinct operating modes: 1) TCC off mode, 2) TCC engage mode, and 3) TCC apply mode.

TCC Off Mode

In the TCC-Off mode the TCC mode valve is turned off and the clutch is fully released. Consequently, the torque converter fluid path is carrying the full torque between the engine and the transmission.

TCC Engage Mode

In the TCC-Engage mode the controller pressurizes the TCC mode valve anticipating that the TCC will carry torque. However, the clutch pressure is controlled to an engage pressure level, P_{eng} , where the clutch is snug, but carries an insignificant amount of torque. Thus, the torque is mainly carried by the torque converter fluid path. In addition under the TCC-Engage mode TCC slip should be close to the slip in the TCC-Off mode.

TCC Apply Mode

The clutch pressure is raised from engage pressure, P_{eng} , to the feedforward pressure, P_{ff} , when the algorithm enters the TCC-Apply mode. The pressure is increased linearly with a slope defined by the constant K_t , or

$$P_{ramp} = P_{eng} + K_t (P_{ff} - P_{eng}) t,$$

where P_{ramp} is the pressure command sent to the torque converter clutch when the increasing the engage to the feedforward pressure and t is time.

Slip feedback compensation is implemented when the TCC P_{ramp} pressure reaches P_{ff} . The feedback pressure term is a function of the slip error, ω_e , defined as:

$$\omega_e = \omega_{TCC} - \omega_d,$$

where ω_{TCC} is the measured TCC slip and ω_d is the desired TCC slip which is a function of engine speed and transmission gear. The TCC slip controller computes the feedback compensation pressure, P_{fb} , as a function of the TCC slip and its integral, or

$$P_{fb} = K_p \omega_e + K_I \int \omega_e dt.$$

In summary, after P_{ramp} is equal to P_{ff} , the pressure command sent to the TCC, P_{TCC} , is the sum of the engage pressure, feedforward pressure, and feedback pressure,

$$P_{TCC} = P_{eng} + P_{ff} + P_{fb}.$$

DRIVELINE TORSIONAL VELOCITY MEASUREMENTS

The vehicle used for testing is a GM all wheel drive (AWD) sports utility vehicle (SUV) equipped with a V-8 engine and an automatic six-speed transmission. Driveline torsional velocity measurements were acquired at the engine flex-plate using a magnetic pickup and at the front and rear propeller shafts (ends closest to the front and rear differentials) using laser vibrometers. The laser vibrometers were targeted at patterns mounted around the ends of the propeller shafts. It should be noted that since the transmission gear states change the transmission dynamics and subsequent vibrations at the propeller shafts, it is necessary to acquire torsional measurements in all the transmission gear states relevant to ECCC.

The torque converter and the TCC used on the vehicle have several design modifications. Because of the superior heat capacity a multi-plate torque converter clutch is used in the vehicle's torque converter. The control of a multi-plate TCC has been a research problem addressed in the literature [7, 8, 9]. Vehicle testing has shown the acceptable performance of the feedback methodology described in the previous section to actively control the torque converter slip using a multi-plate TCC. A modification can also be made in the location of the torque converter isolator. As shown in Figure 2(a), the conventional location of the isolator, denoted in this investigation as a regular damper, is between the TCC and the input shaft to the transmission. However, the location of the isolator, denoted in this investigation as a turbine damper, can also be placed between the turbine and the input shaft to the transmission. The modified location of the isolator is shown in Figure 2(b). On the vehicle, both isolator configurations were tested. The characteristics in terms of travel distance and stiffness of both isolators tested were similar.

In this investigation three vehicle and torque converter configurations were tested:

1. All wheel drive configuration and a multi-plate TCC with a regular damper (see Figure 2(a)),
2. All wheel drive (AWD) configuration and a multi-plate TCC with a turbine damper modification (see Figure 2(b)), and

3. Rear wheel drive (RWD) and multi-plate TCC with a turbine damper modification (see Figure 2(b)).

Although testing could be done in all transmission gear states relevant to ECCC, only results for second, fourth, and sixth gear are shown in this investigation as they are sufficient to analyze the effects of using closed-loop TCC slip control on the torsional velocity amplitude.

Vehicle testing was conducted on an all wheel drive chassis dynamometer. The tests consisted of maintaining a constant load at the wheels while increasing the engine speed from 800 to 3000 revolutions per minute (RPM) or 60 to 200 Hz (to convert the speed to firing frequency in Hz, the engine speed in RPM must be divided by a factor of 15 since the speed must multiplied by 60 to convert it to revolutions per second and the engine fires 8 times every 2 revolutions). Since the objective of this investigation is to evaluate the effects of ECCC and different TCC isolator configurations, shown in Figure 2, the lower axle frequency is not considered. The tests were done for low, medium, and high dynamometer loads. The relationship between the wheel loads is the following: the medium load is two times the low load, while high load is 3.00 times the low load. The frequency content of the driveline torsional velocity measurements was analyzed and the magnitude of the torsional velocity frequency component corresponding to the engine's firing frequency was calculated. Although the engine pulses do excite other frequencies, the most significant effect of torque converter slip on vibrations is at the engine's firing frequency. The torsional velocity magnitude determined by the measurements is expressed in terms of the torsional velocity ratio (TVR) defined as:

$$TVR = \frac{\delta}{\delta_{ref}},$$

where δ is the calculated torsional velocity amplitude which is normalized by an a priori defined torsional velocity amplitude δ_{ref} .

ALL-WHEEL DRIVE CONFIGURATION

Figure 3 shows the torsional velocity measurements for the transmission in second gear (gear changes are disabled using the transmission software), under a medium wheel load, and for four types of torque converters slips. In the figure, the torsional velocity magnitude is shown against the engine firing frequency. It should be noted that the torsional velocity amplitude data shown in all the figures in this investigation correspond to the measurements at the end of the rear propeller shaft. As would be expected, the torsional velocity amplitude is highest and lowest for a locked and open torque converter clutch respectively. The measurements also show that presence of two resonant peaks at around 80 and 130 Hz. The results of the