Challenges and Opportunities in Automotive Transmission Control

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Abstract: Automotive transmission is a key element in the powertrain that connects the power source to the wheels of a vehicle. To improve fuel economy, reduce emission and enhance driving performance, many new technologies have been introduced in the transmission area in recent years. This paper first reviews different types of automotive transmissions and explains their unique control characteristics. We then address the challenges facing automotive transmission control from three aspects: calibration, shift scheduling, and sensing, actuation and electronics. Along the way, research opportunies to further improve system performance are discussed.

1. Introduction to the Latest Automotive Transmission Technologies

To improve fuel economy, reduce emission and enhance performance, automotive manufacturers have been developing new technologies for powertrain systems. In the transmission area, emerging technologies [1] such as continuously variable transmission (CVT), dual clutch transmission (DCT), automated manual transmission (AMT) and electrically variable transmission (EVT) have appeared in the martket, which is traditionally dominated by step gear automatic transmission (AT) and manual transmission (MT). Among many different technical challenges for developing these new transmissions, system dynamics and control are crucial to realizing the fuel economy and emission benefits while providing superior performance.

The basic function of any type of automotive transmission is to transfer the engine torque to the vehicle with the desired ratio smoothly and efficiently. The most common control devices inside the transmission are clutches and hydraulic pistons. Such clutches could be hydraulic actuated, motor driven or actuated using other means (see Figure 1). Therefore clutch/piston control is essential for transmission operation. In both DCT and AMT, clutch control is the key to ensure smooth torque transfer. In CVT, hydraulic piston control is crucial for not only system performance but also device durability. In many of the new automatic transmissions (AT), clutch-to-clutch shift is adopted to reduce the cost and improve packaging. This involves electronic control of both the oncoming and offgoing clutches and the timing and coordination between them. In addition to eliminating the shift valves, accumulators, etc., clutch-to-clutch control eliminates the coasting clutches and freewheelers, greatly simplifying the transmission mechanical content. The absence of these devices makes the robust control of clutch-to-clutch shifts a challenge.

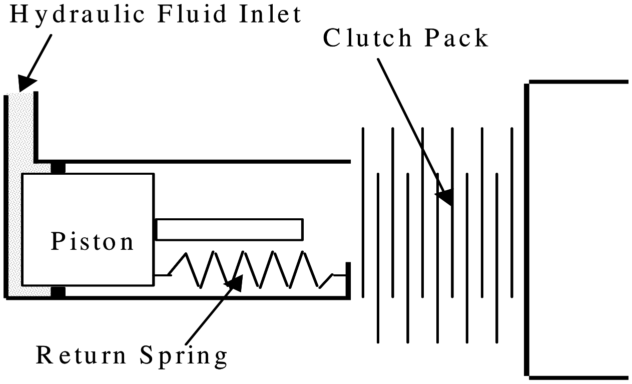

Figure 1. Schematic Diagram of a Clutch

With the traditional control system in an automatic transmission with clutch-to-clutch shifts, the oncoming clutch fill process is a major source of uncertainty and it makes the clutch coordination during the shift a difficult task. The fill time of the oncoming clutch varies due to many factors, such as, fluid temperature, solenoid valve characteristics, line pressure variations, and time elapsed between shifts. The commanded fill pressure and the commanded fill time are critical to achieving a good fill and a smooth start to the shift process. Even small errors in calculating these two parameters could lead to an overfill or an underfill, as shown schematically in Figure 2. Some algorithms have been developed to detect the end of fill using speed signals, but none of them has proven reliable and fast enough to prevent

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overfill spikes. An example of an oncoming clutch overfill during an upshift is shown in Figure 3. The oncoming clutch pressure shows a slight overfill, which results in shift tie-up, causing engine pull down and a big drop in the output torque. A more robust offgoing clutch control was necessary in this example to avoid a tie-up. While the overfill can be corrected using adaptive schemes for future shifts, the real challenge is in preventing it from happening in the first place.

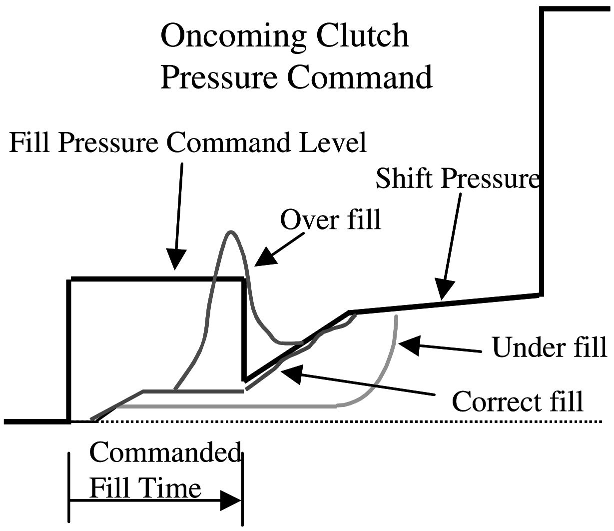

Figure 2. Variations in Clutch Fill Process

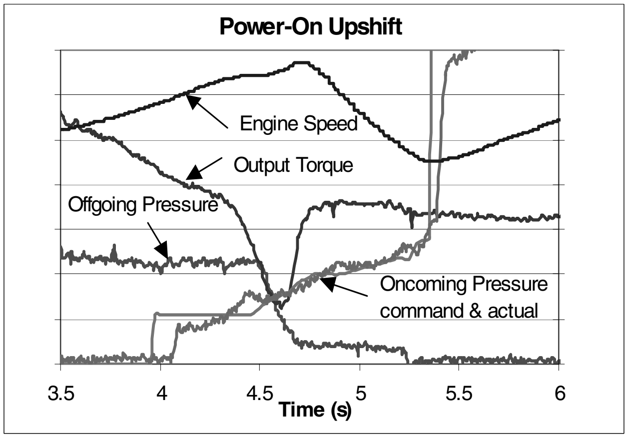

Figure 3. Effect of Clutch Overfill on an Upshift

Currently in most clutch-to-clutch shift production transmissions, the clutch coordination is accomplished by a combination of open-loop, event-driven, and feedback control schemes. Transmission input and output speeds are the primary measured variables used in this control. An adaptive system is used to compensate for shift-to-shift variations and build-to-build variations [2]. Recently, an integrated torque based approach using both engine and transmission handles has been proposed. The main difficulty with the torque approach has been in the area of clutch coordination and consequently, consistent shift quality.

The automated manual transmissions (AMT) have become popular in Europe. In North America, their potential use is limited because of the torque interruption during shifts that is inherent to their designs. An offshoot of the AMT is the dual input clutch transmissions (DCT), which use two input clutches – one for odd gears and one for even gears. DCTs can transmit torque continuously through the shift. All the control issues and challenges during launch and shifts confronting the friction launch transmissions (FL) are also inherent to DCTs. A DCT requires much more calibration work than conventional torque-converter automatics and would be expected to be less refined in driveability, even in production. On the other hand, because DCTs have more calibration handles, they can be varied to fit different vehicle specifications and different driving conditions. One of the control challenges with torque-converter-less transmissions such as DCT and FL is highlighted in Figure 4. With an undamped driveline, a transient such as a shift event could trigger undesirable oscillations in the driveline, as indicated by the output torque trace.

In a friction launch (starting clutch) transmission, the absence of the torque converter leaves the driveline with no hydraulic damping, and consequently, poses many control challenges including vehicle launch feel, undamped behavior during shifts and tip-in / tip-out maneuvers. Without using expensive torque or pressure sensors, the control of a clutch emulating a torque converter is a major challenge. Both hydraulic clutch [3] and magnetorheological fluid clutch implementations have been investigted by researchers.

Continuously variable transmissions (CVT) enable the engine to operate in a wide range of speed and load conditions independently from the speed and load requests of the vehicle [4]. This feature allows the engine to operate in the optimal region virtually independent of the vehicle speed to maximize the fuel efficiency. Different types of CVT have appeared in the market. The belt and chain drive CVTs use the hydraulic piston to control the sheave position and thus the input-output ratio. The major control challenge is to maintain optimal clamping force to prevent slipping while providing fast ratio control to maximize the fuel economy benefit. Toroidal traction drive transmissions (TCVT) have been examined by many manufacturers as promising alternatives to chain or belt CVTs. TCVTs offer a larger torque capacity and a quicker ratio change capability. A half-toroidal CVT system is unstable under open-loop operation and hence a speed ratio control system is necessary [5]. In addition, when a CVT incorporates the geared neutral concept, it eliminates the need for launching devices, such as torque converters and slipping clutches. At the geared neutral point, speed ratio control becomes inadequate and output torque control is required. The control challenges in a TCVT are highlighted in [6-7].

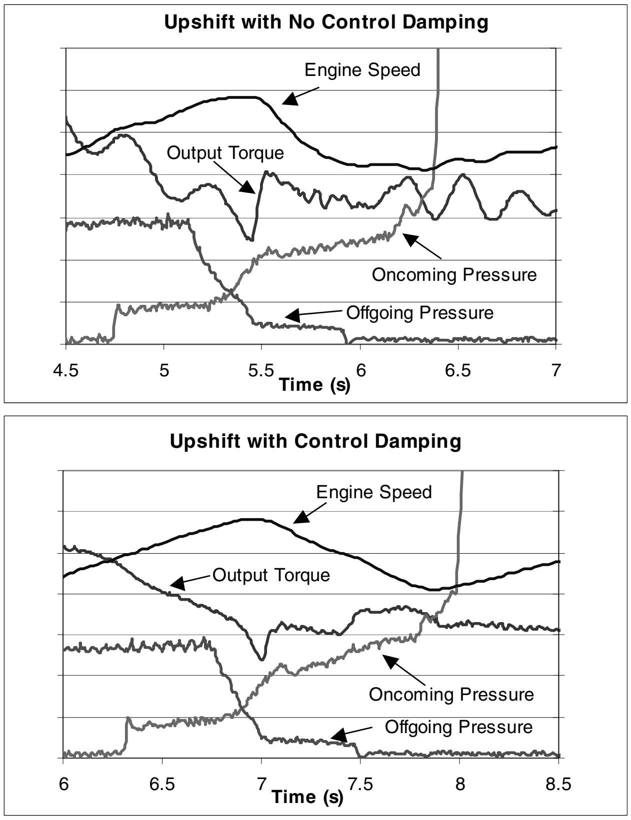

Figure 4. Effect of Controlled Damping after an Upshift

Electrically variable transmissions (EVT) have appeared in the market recently. The advantages of using electric machines, namely motors/generators, with planetary gear sets include flexibility, controllability, and better performance. Great efforts have been made to extend speed ratio coverage by exploring various planetary gear train arrangements and by exploring regime shift similar to that used in step transmissions. These designs, in general, are quite complex in construction as they involve a number of planetary gear sets and clutches. Elaborate control schemes are required to ensure synchronized regime shift and avoid abrupt torque changes at the output during shifting [8-9]. The control algorithms will ultimately determine how drivers perceive hybrid vehicle performance, particularly whether they notice when the vehicle switches back and forth between the electric motor and the engine. Hybrid vehicles may just be a stop-gap technology before conventional internal combustion engines are replaced by fuel-cell propulsion systems. In fuel-cell vehicles, electric motors inside the wheels may completely eliminate the need for transmissions and change the dominant technology in the future [10].

2. Transmission Control Algorithms and Hardware Development

Look-up tables with calibrated variables are widely used in automotive transmission control. With the increased functionalities and electronic components, system calibration complexity goes up quickly. This is caused not only by the electronic control of the transmission, but also the coordination with engine and other components in the driveline. For example, with the increasing number of gear ratios in automatic transmissions, the number of variables to be calibrated to realize smooth shifts under all driving conditions goes up quickly. To greatly reduce the development time and improve performance, an automated and systematic approach is required for the calibration process. First, automated tuning process was investigated to calibrate the transmission automatically with little or no human interference. An automated tool set was developed to calibrate automotive powertrain without human-in-the-loop [11]. An adaptive online design of experiments (DOE) approach was developed for GDI engine calibration [12]. This approach enables the efficient experimental design for nonlinear systems with irregularly shaped operating regions. The same principle can be applied to the automotive transmission calibration. Second, model based control was proposed as an enabler to reduce the number of calibration variables and consequently, the calibration effort and time. However, the uncertain environment and wide operation range present a major challenge to system robustness. The transmission temperature can vary from –40 degree C to 150 degree C, which in turn affects the automatic transmission fluid (ATF) properties. The wide range of operation from completely stopped to rotating at high speed with high load demands precise models and high bandwidth controls. Reference [13] described procedures for determining a set of linearized models and the associated unmodeled dynamics for the torque converter clutch in the automatic transmission and applied robust control design to achieve desired performance. Detailed procedures for the development of transmission models for controlling the inertia phase during a shift were presented in [14]. Based on these models, robust control can be designed to achieve desirable shift performance regardless of the engine load, ATF viscosity, etc. Variable structure control (VSC) was also investigated for clutch control in an automated manual transmission [15]. Results show that VSC control is able to maintain system robustness within the uncertain environment. Third, adaptive learning control was developed to accommodate the uncertain environment and different driving patterns. Artificial neural network (ANN) was employed to model the automotive powertrain using the black-box approach [16]. Input and output data are used to train the ANN to emulate the functions of the transmission and its subsystems. A distinctive feature of this approach is that it can emulate not only the steady state operation but also the dynamic/transient operation of the system. The key advantages of this approach include online training using real-time vehicle data and adaptive calibration or control capability.

As more number of speeds is added to the transmissions, shift schedule gets more complicated. Since traditional shift schedule only considers vehicle speed and throttle angle to determine shift points, shift busyness has become a concern under certain road conditions, such as hilly terrains. For example, during a winding uphill driving, the driver releases the gas pedal before entering the curve to reduce vehicle speed, and traditional shift schedule may perform an upshift in response to the throttle change. But right after the curve, the driver needs to step into the gas pedal to increase vehicle speed and a down shift may then be executed. Similarly during a downhill driving, an upshift is performed by the traditional shift schedule when throttle angle is decreased, thus unpleasantly reducing the engine brake. By including factors such as road grade, steering angle, vehicle acceleartion, etc., flexible shift schedule that is pleasing to the customers and favorable for fuel economy must be developed. Shift busyness avoidance control using fuzzy sets and neural networks have been investigated in the past [17-18]. Most of the adaptive shift point algorithms presented in the literature require some knowledge of the mass of the vehicle and the gradient of the road on which the vehicle is travelling. A reliable mass estimation algorithm is lacking in the literature. With good mass information, the estimation of the road grade is straight forward. Recently vehicle navigation system was used to provide some preview information on the road shape and conditions during the shift scheduling process [19]. Recent work [20] on shift scheduling also added feedback learning to the fuzzy logic system to update the membership function in real-time to better accomodate different driving patterns. They also extended the work to include not only the AT, but also the AMT, DCT and CVT. A block digram summarizing the general structure used in gear shift scheduling is shown in Figure 5.

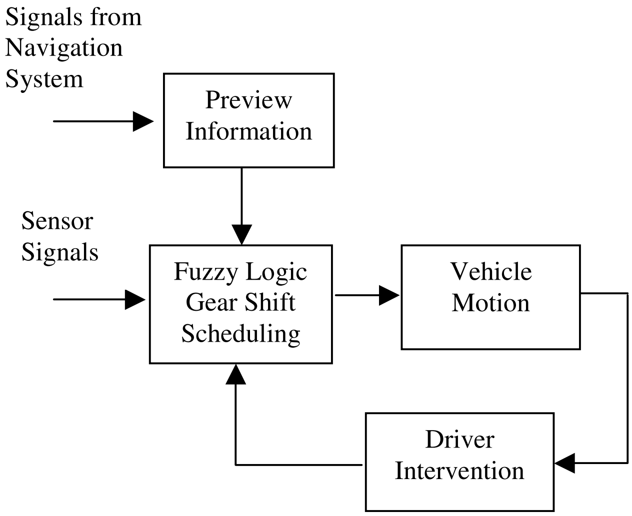

Figure 5. Block Diagram of the Gear Shift Scheduling Algorithm

To accommodate the ever-increasing demand for computational power, sensing and actuation capabilities, transmission control hardware has been undergoing many changes. Those changes involve all three levels of complexities: the sensing level, the actuation level, and the system level. At the sensing level, new sensing technologies have been pursued to either improve the performance and efficiency of current hardware or enable new actuation technologies. Pressure switches and temperature sensors are used in current production transmissions. To optimize transmission operation, pressure sensor and torque sensor are desirable. The main challenges for introducing these sensors into production units are cost and durability. A piezoresistive semiconductor pressure sensor was evaluated for automotive applications [21]. It claims to measure pressures up to 3.5 Mpa within +/- 1% of the full scale. Early work on torque sensors can be traced back to early 80s when researchers [22] investigated a non-contact miniature torque sensor for automotive transmissions. Recently magnetoelastic torque sensors have been investigated by a number of researchers [23-24]. The phenomenon of inverse-magnetostriction that converts material strain into magnetic property changes was exploited to measure transmitted torque. To overcome the harsh environment inside the transmission, special coating technologies were developed to protect the sensing element. A clutch disk integrated torque sensor was also proposed for automotive applications [25]. The sensing elements are integrated in the clutch plate to achieve precise and robust measurement. At the actuation level, solenoid valve control technologies were investigated to improve controllability and flexibility of the hydraulic system. For clutch actuation, variable bleed solenoid (VBS) valves are widely used now in place of the pulse width modulation (PWM) valves for better controllability. However, VBS valves suffer from hysteresis and variations due to temperature. Analytical modeling of proportional control solenoid valves was conducted using system identification theory [26]. It concludes that the valve bandwidth was limited by the bandwidth of the electromagnetic portion of the solenoid. To further enhance system performance, fast and precise valve actuation devices are needed. A new concept [27] for an on/off valve with rotary actuator was proposed to handle flow rate greater than 10 lpm with less than 5 ms response time. A key feature of this concept is that the valve has a single stage construction, but performs as a two-stage valve. Alternative clutch actuation technologies were also pursued to replace the electro-hydraulic actuators in automatic transmissions to improve fuel economy and performance. Motor driven clutch actuation has been investigated by a number of researchers [28]. The major challenges for the electromechanical actuators are the low power density and available electrical power inside the vehicle. Usually some kind of gearing is required to amplify the torque capacity of the motor. Smart material based clutch actuation devices were also developed by a number of researchers. Feasibility of using electrorheological (ER) fluid clutch inside automotive transmission was investigated and desirable properties of ER fluid were proposed for future research [29]. Magnetic powder clutch was used as a starting clutch for a CVT equipped vehicle [30]. Potential applications of magnetorheological (MR) fluid clutch were discussed in [31]. At the system level, there is a new trend of migrating the control electronics from passenger compartment to the transmission case or even integrate the electronics inside the gear box to reduce cost and improve performance and quality [32-33]. A new terminology called mechatronic transmission [34] was coined recently to illustrate the integration of control electronics with the transmission device itself. Besides cost and quality benefits, this approach will enable the testing and calibration of the transmission devices right on the assembly line. To enable the gearbox-integrated electronics, new electronic integration and packaging technologies were also investigated to overcome the harsh environment inside the gearbox [35].

3. Conclusions

In order to realize maximum fuel economy benefit and provide superior performance, research and development in both control software/algorithm and hardware are required for the automotive transmissions. With the enhanced functionality and increased complexity in both software and hardware, system integration is the key for successful transmission development.

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