

Sliding Mode Adaptive PID Control of an Automotive Clutch-By-Wire Actuator

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ABSTRACT

Dry clutch control is one of the main components of both conventional and advanced automotive powertrain systems. In this paper, a robust control strategy is proposed which is suitable for the precise and accurate control of a clutch-by-wire actuator in automotive applications. A parallel connection of a sliding mode controller to a proportional integral derivative (PID) controller collectively forms the proposed robust controller. The sliding mode controller alone ensures robust control against system nonlinearities by providing a high feedback gain, but it also induces a control chattering phenomenon which could be harmful for the clutch-by-wire actuator. Instead of viewing chattering as an undesirable yet inevitable feature, the chattering signals are used as natural excitation signals for identifying an equivalent PID controller using the recursive least squares algorithm. Analysis is provided on the robustness properties of the control scheme. Simulation results of the proposed controller for a clutch-by-wire actuator are presented using a highly realistic clutch-by-wire system mathematical model. The simulation results demonstrate that the proposed control approach has achieved excellent performance indices while at the same time damp the chattering signal commonly encountered in sliding mode techniques.

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INTRODUCTION

A Vehicle's transmission is one of its most important components as it has a significant impact on both performance and fuel economy. Both automatic and manual transmissions have their benefits, but both also have some disadvantages. The manual transmission (MT) is the most efficient transmission available. The efficiency of the manual transmission is dependent on the load applied. Over a representative drive cycle its efficiency can approach 97%. In automatic transmission (AT), a reduced performance and fuel economy is apparent because of its lower efficiency. Not only are there parasitic losses to account for to operate the hydraulic pump, but large amounts of slip in the torque converter generates heat loss which warms the transmission fluid rather than provide torque to the wheels. Over a representative drive cycle the efficiency of an AT can be as high as 86% [1].

An Automated Manual Transmission (AMT) system combines the major benefits of automatic and manual transmissions. The AMT provides the ease of use of the automatic transmission and the efficiency and fuel economy of a manual transmission. A vehicle with AMT system achieves a faster 0-100 km/h acceleration and a better fuel economy rating [2]. This is due to the ability to easily control the transmission shift pattern and operate the engine at its peak efficiency for a longer period of time as well as eliminating some of the parasitic losses common to automatic transmissions.

In AMT systems, actuators are added on a conventional manual transmission to control both the dry-clutch and gearbox. Electro-hydraulic actuators are sometimes used to achieve this task [3], [4] but

the most common type used in the control action of both the dry-clutch and the gearbox is the electro-mechanical one [5], [6], [7], [8]. The electro-mechanical actuator commonly consists of a DC motor coupled to a rotary to linear motion mechanism (i.e., power screw-nut mechanism). The first generation AMT had excellent fuel efficiency, but poor shifting quality [9] [10]. The first automatic manual clutch was introduced by Mercedes in the 1950's. The clutch was actuated when the driver touches the shifting lever. Some vehicles using AMT are BMW, Mercedes, Alfa Romeo 156, VW Lupo 3L, and Audi A4. [4]. AMT systems are gaining world wide attention and are even utilized in newly developed hybrid vehicles [5],[7].

Mechanically driven dry clutch is one of the main components of vehicle powertrain system. Before any shift changes of the vehicle manual gearbox, engine power has to be insulated from the rest of the powertrain system by the disengagement of a dry-clutch. Similarly, an electronically controlled clutch or automated manual clutch (commonly called clutch-by-wire) is one of the basic components of AMT systems. The clutch engagement must be controlled in order to satisfy different and conflicting objectives: driver comfort by avoiding powertrain torque interruption, good powertrain performance (minimum shift time) and small friction losses. Consequently, the engagement control of automated dry clutches is becoming more and more important.

Due to the many useful avenues that the clutch-by-wire system can provide, many different approaches for the control of dry clutch engagement have already been investigated. The engine control problem is treated using a PI decoupling controller for the engine and clutch torques to ease the engine control problem [11] or by

introducing a PID controller based on a powertrain linear model [12]. Another approach is the utilization of an insulated engine throttle control technique [13]. High level of powertrain nonlinearity could be handled using two piecewise linear time-variant models of the automotive drive-line where a slip control technique for the dry clutch engagement process is introduced [14], [15] or by using a flatness based control approach with nonlinear feed-forward combined with a linear feedback control strategy [16]. To avoid dealing with the nonlinearity of the powertrain model, a supervisory fuzzy logic controller is proposed in [17] based on a sixth order state space model of the powertrain. Another approach of dry clutch control based on a dynamic model of the clutch and an estimation of engine output torque is presented [18]. The comfort optimization challenges are illustrated where an optimal controller is used to minimize the powertrain torque interruption [19]. Optimal control strategies are used to enhance powertrain performance while keeping the torque interruption to a minimum level [20], [14], [21], [22]. Robustness of the slide mode control techniques are expected to handle different type of electro-mechanical systems non-linearities / disturbances [23]. Treating the powertrain clutching process as a variable structure system and using of sliding mode control techniques are proven to be efficient in compensating for system non-linearities [8], [24], [25], [26], [27], [28]. On the other hand, control signal chattering which is induced due to the high gain of the sliding mode relay need to be treated for safe actuator control elements operation.

From the previous review, it can be seen that the automated dry-clutch in automotive applications faces many challenges such as torque interruptions which lead to uncomfortable vehicle acceleration and jerks. Uncomfortable acceleration means there is discontinuity in the acceleration time curve. This leads to reduced comfort and loss of tractive force from the engine during shifting which leads to shift shocks. These main issues are generally related to the clutch nonlinear torque transmission behavior. The interruption of the dry clutch transmitted torque could be related to two main clutch non-linearities in the engagement / disengagement process. First, the nonlinear friction coefficient of the clutch disk friction material which is investigated and treated by the author in previous work [29]. Second, the non-linear behavior of the clutch diaphragm spring.

Since interruption of driving torque transmission occurs in the clutching action, the clutch actuator control needs high accuracy and fast response. In order to solve the formentioned problem, improvements of the robust stability against different system non-linearities / disturbances is a key issue.

In this work, a dry-clutch electro-mechanical actuator and its robust control is presented. The proposed control system involving a sliding mode parallel with a PID controller. The sliding mode technique is selected due to its well-known robustness against system non-linearities. The chattering signal encountered as a consequence of the sliding mode is used to automatically tune an equivalent robust PID controller which may then replace the parallel Sliding Mode-PID controller and at the same time eliminates the chattering signal that may be harmful to the actuator.

CONVENTIONAL AND ADVANCED AUTOMOTIVE POWERTRAIN SYSTEMS

Figure 1 shows the architecture of the Automated Manual Transmission (AMT) system which could be considered one of the most common advanced powertrain systems currently available in automotive applications. AMT systems in their simple form can be considered as an automated conventional powertrain system. In the conventional systems the vehicle driver has to control both the clutch and the gearbox shift in an intuitive way based on his driving experience. In AMT systems electro-mechanical or electro-hydraulic actuators are used to actuate and synchronize the control of both the clutch and the gearbox shifts. As shown in Figure 1, the system Electronic Control Module (ECM) receives different types of signals and sends activation commands to the clutch and the gearbox shift actuators which ensure efficient vehicle powertrain system control at different vehicle operating conditions.

The clutch is used to gradually engage the engine to the powertrain while avoiding unpleasant shocks, jerks (powertrain torque interruption) and excessive clutch wear. In summary, the objectives of the clutch control are to: a) smooth the connection between two rotating masses, the engine flywheel and the gearbox transmission shaft, b) avoid engine stall (or engine kill zone), c) minimize shift time by reducing the engagement time.

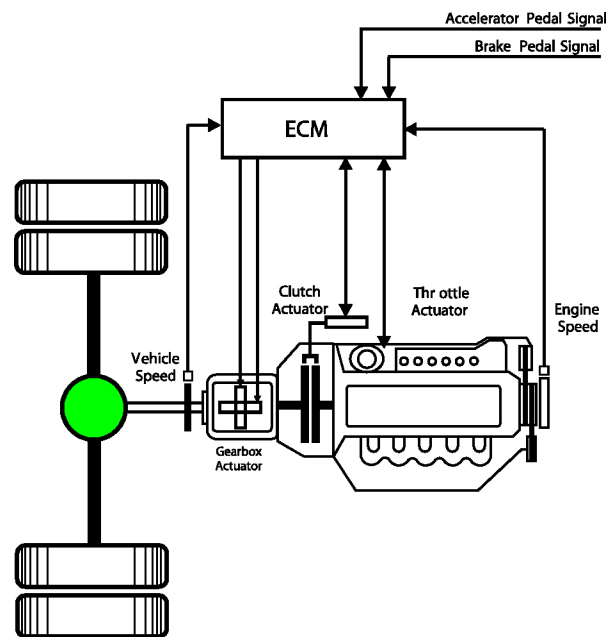


Figure 1. Advanced Automated Manual Transmission System Configuration.

The clutch actuation has to satisfy these conflicting goals of minimizing engagement time and in the same time avoid powertrain torque interruption. That is why the clutch control could be considered one of the most critical element in powertrain control system and extensive study of the clutch engagement characteristics and its impact on overall system performance could be very useful in powertrain system design and control development efforts.

THE DRY-FRICTION CLUTCH ENGAGEMENT SYSTEM

The automotive dry-friction clutch, shown in Figure 2, consists of a housing, pressure plates, friction plates, a clutch disk with torsional dampers and release mechanism. The clutch disk is mounted onto the transmission input shaft and is radially fixed by the splines interface. The clutch is normally engaged, as the diaphragm spring is pre-tensioned when assembled. Figure 3 shows the displacement-force non-linear relation of the clutch diaphragm spring stiffness which is common nonlinearity in the clutching process.

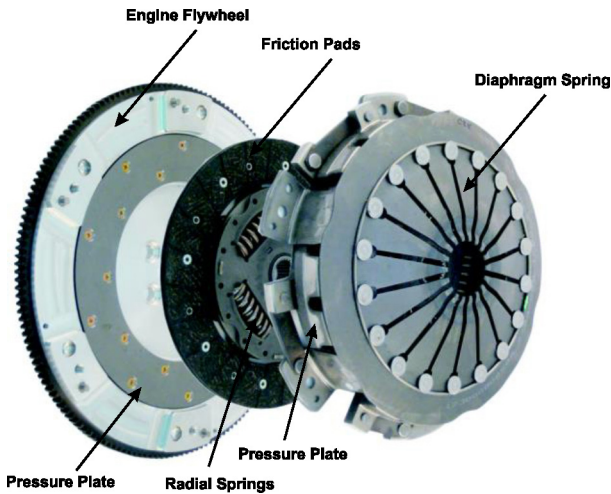


Figure 2. Dry-Clutch Main Components

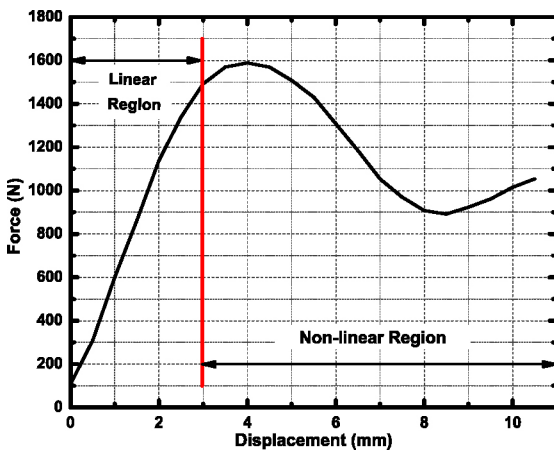


Figure 3. Clutch Diaphragm Spring Stiffness

The axial bearing can slide on the transmission input shaft and push against the diaphragm spring. The direction of the release force is swapped through the lever joints and releases the pressure from the clutch disc, which is then able to rotate independently from the engine. Furthermore, the disc is equipped with radial torsional springs and work as a torsional dampers, which consist of a complex assembly of coil springs in parallel and in series. The purpose of these springs is to maximize driver comfort during clutch engagement and disengagement. The flat spring (also called cushion spring), is a thin steel disk placed between friction pads and is designed with different radial stiffness in order to ensure the desired smoothness of engagement.

AUTOMATED DRY-CLUTCH ELECTRO-MECHANICAL ACTUATOR

Figure 4 shows the layout of the proposed dry-clutch electromechanical actuator. The system consists of screwnut mechanism driven by a geared DC motor. The actuator is able to produce an actuation force of 1960 N maximum with a speed of 0.1 m/s. The maximum actuator displacement is 50 mm. These design values are insured to cover a wide range of passenger vehicles and in city trucks.

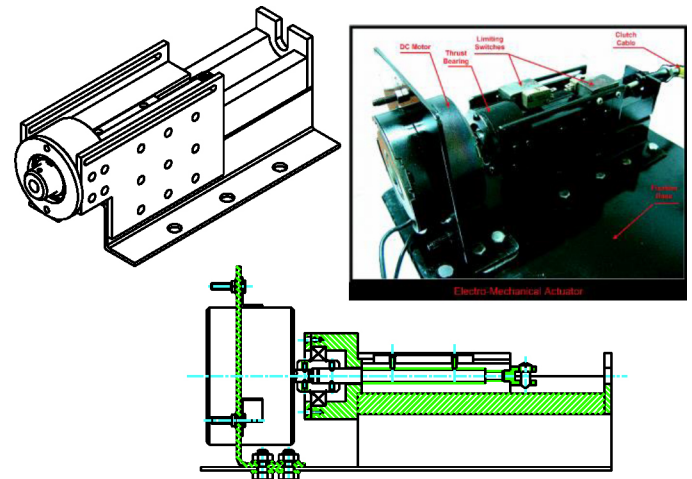


Figure 4. Proposed Automated Dry-Clutch Electro-Mechanical Actuator

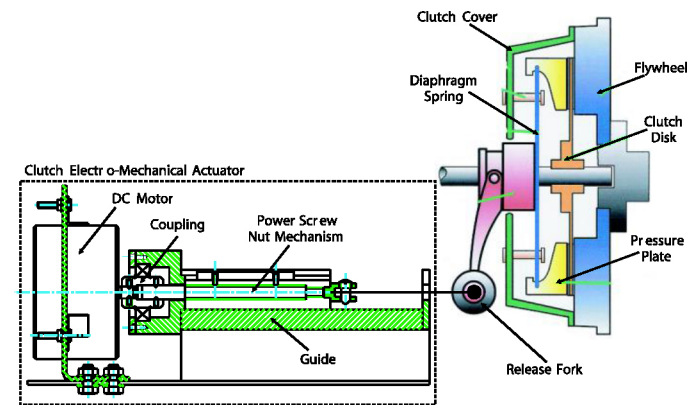


Figure 5. Clutch-By-Wire System Configuration

These design values are determined by experimental work which is carried out on a sample of these types of vehicles. A linear position sensor is used to provide the feedback signal for the actuator displacement.

MODELING OF THE PROPOSED DRY-CLUTCH ELECTRO-MECHANICAL ACTUATOR

The proposed system configuration is shown in Figure 5. The electromechanical actuator is connected to the clutch through the release fork. The electro-mechanical actuator moves the clutch fork which controls the clutch diaphragm spring causing the clutch to engage or disengage. The clutch fork resisting force is a non-linear function of the