

Torque Control of Rear Wheel by Using Inverse Dynamics of Rubber/Aramid Belt Continuous Variable Transmission

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ABSTRACT

This paper concerns a torque control of a rear wheel of a motorcycle equipped with a rubber/aramid belt electronically-controlled continuous variable transmission where a primary sheave position is controlled by an electric motor. In particular, the paper discusses a method to calculate a required engine torque and a required primary sheave position, given reference values of a rear-wheel torque and an engine rotational velocity. The method forms a foundation of a hierarchized traction control where a higher control layer decides an optimal motorcycle motion (rear-wheel torque and engine rotational velocity) and a lower control layer realizes the motion by actuators (engine torque and primary sheave position). Difficulties of the control are due to large mechanical compliance of the rubber/aramid belt, which leads to an inevitable lag from the primary sheave position to a speed reduction ratio. Taking into account the compliance, the proposed method compensates rotational kinetic energy and losses of the transmission to improve accuracy of the control.

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INTRODUCTION

Background

This paper concerns an integrated control of an electronically-controlled continuously variable transmission (ECVT) and an electronically-controlled throttle valve (ETV). In particular, the paper discusses a method to compute a required engine torque and a required primary sheave position, given a required rear-wheel torque and a required engine rotational velocity.

The ECVT is one of good ways of balancing low fuel consumption and high acceleration [1]. Especially, the ECVT with a rubber/aramid belt is lightweight and compact, hence it is adopted for motorcycles widely [2, 3, 4]. On the other hand, the ETV allows greater flexibility to control an engine torque. Recent technological developments of fast-response ETVs have increased adoption examples in motorcycles [5].

An integrated control of the ECVT and the ETV has possibility to achieve a better balance between low fuel consumption and high acceleration. Actually, it has been a prevalent technology in four-wheel automotives. However, it has never been adopted yet in motorcycles, though it is also a promising technology for motorcycles.

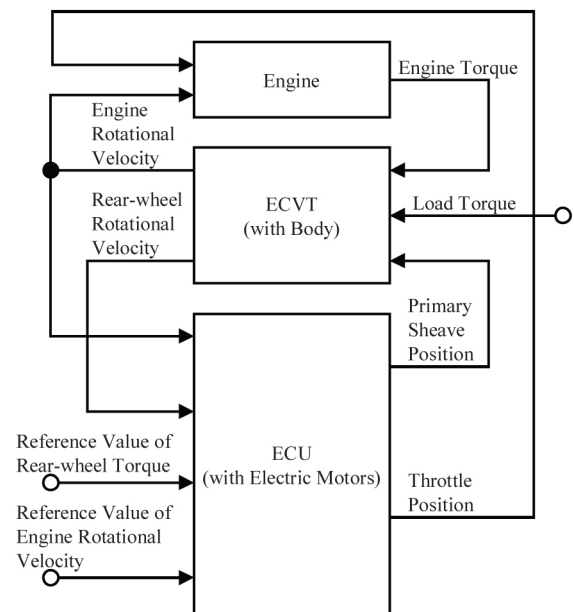


Figure 1. Overview of Control System

One of its possible problems is the acceleration, which is directly linked to safety in the motorcycles. Deadtimes, lags, and overshoots of the acceleration could destabilize motions of the motorcycles and they could deteriorate the safety. To avoid the destabilization, the motorcycles require a delayless and errorless control of the acceleration.

Problems

This study formulates a driver demand for the acceleration as combination of a reference value of a rear-wheel torque and a reference value of an engine rotational velocity.¹ To achieve the reference values, the controller changes the engine torque and the primary sheave position to achieve the reference values.

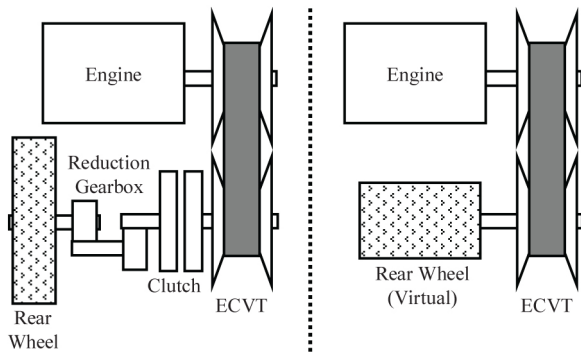


Figure 2. Mechanical System of ECVT

Suppose that the control system realizes the reference values of the rear-wheel torque and the engine rotational velocity in a given driving condition. When the reference values are changed by the driver demand, the controller changes the engine torque and the primary sheave position to achieve the reference values. However, the following factors prevent the control system from achieving the reference values.

1. A virtual moment of inertia about a crankshaft is continuously-varying.
2. A transient response of a speed reduction ratio is different from its quasi-static response. The difference is due to a belt elongation and a belt width contraction.
3. A transmission efficiency is time varying. It depends on a load torque and speed reduction ratio.

The above three factors are not negligible in the ECVT with the rubber/aramid belt. A controller design must consider the factors to realize the driver demands without delay or error.

Novelty

This paper focuses on dynamics of the ECVT; the ECVT is a three-input/two-output dynamical system (Fig. 1): the inputs are the primary sheave position, the engine torque, and a load torque, and the outputs are the engine rotational velocity and the rear-wheel rotational velocity. We derive an inverse system from the dynamical system and adopt it as the controller which compensates the above three factors, that is, as the controller that achieves the reference values of the rear-wheel torque and the engine rotational velocity without delay or error. The key point is an order reduction of the ECVT; this paper approximates the ECVT by a six-dimensional dynamical system, although the ECVT is an infinite-dimensional dynamical system. Herewith, the controller can be implemented as a six-dimensional dynamical system, which is simple enough for embedded computers to calculate the dynamics in real time.

Organization

In Chapter 1, our background, problems, and novelty were explained. In Chapter 2, we formulate the problem and illustrate our solution. In Chapter 3 and Chapter 4, the ECVT model and the controller are derived. Chapter 5 is a conclusion of this paper. In the appendix, variables used in the paper are enumerated for reference.

PROBLEM FORMULATION

Mechanical System

Figure 2 shows a real structure and simplified model of the ECVT. The crankshaft is connected to the clutch-inner via the ECVT and the clutch-outer is connected to the rear wheel with a fixed reduction ratio (Fig. 2-left). This paper, considering the case of clutch-meet, assumes that the crankshaft is connected to the virtual rear wheel via the ECVT (Fig. 2-right). In the model, a moment of inertia of the virtual rear wheel is adjusted to keep the moments of inertia about the axes of the ECVT. Moreover, a radius of the virtual rear wheel is also adjusted to keep the velocity of the motorcycle.

Control System

Figure 1 illustrates the control system, which consists of three subsystems: the engine, the ECVT, and the electronic control unit (ECU). The system is designed to make the engine rotational velocity and the rear-wheel torque track the each reference value.

The engine is a two-input/one-output system: the inputs are the engine rotational velocity and the throttle position, and the output is the engine torque. The ECVT is a three-input/two-output system: the inputs are the primary sheave position, the engine torque, and the load torque, and the

¹ A reference value of an engine rotational velocity is essentially identical to a reference value of a speed reduction ratio, since a speed reduction ratio is directly derived from an engine rotational velocity and an rear-wheel rotational velocity.

outputs are the engine rotational velocity and the rear-wheel rotational velocity. The ECU is a four-input/two-output system: the inputs are the engine rotational velocity, the rear-wheel rotational velocity, the reference value of the engine torque, and the reference value of the rear-wheel torque, and the outputs are the throttle position and the primary sheave position.

ECU

The ECU is designed so that the rear-wheel torque and the engine rotational velocity track the each reference value without delay or error. To this end, we decompose the ECU to two subsystems. The one is an inverse system of the engine, and the other is an inverse system of the ECVT.

The inverse system of the engine is implemented as inverse of a map from the engine rotational velocity and the throttle position to engine torque. It calculates a reference value of the throttle position from the reference value of the engine torque, given the engine rotational velocity.

The inverse system of the ECVT (Fig. 3-lower) is derived from the dynamics of the ECVT (Fig. 3-upper). It computes the reference values of the engine torque and the primary sheave position from the reference value of the rear-wheel torque, given the engine rotational velocity and the rear-wheel rotational velocity. The computation is based on the fact that the rear-wheel rotational velocity is constant if the rear-wheel torque is equal the load torque. Hence, assuming

1. the rear-wheel rotational velocity is constant,
2. the load torque is equal to the reference value of the rear-wheel torque,
3. and the engine rotational velocity is equal to its reference value,

we can solve the reference values of the engine torque and the primary sheave position.

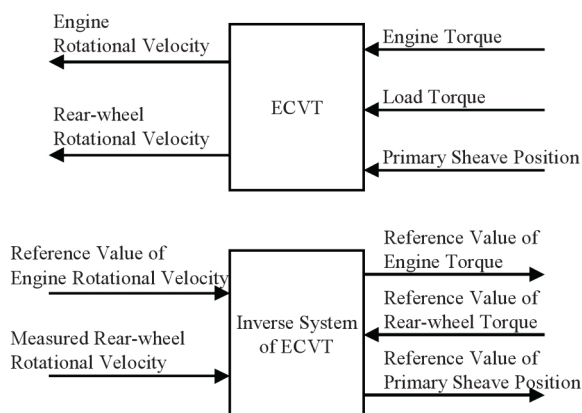


Figure 3. Inverse System of ECVT

MODEL OF ECVT

This chapter details the dynamics of the ECVT. The controller, explained in Chapter, is derived from inverse of the dynamics.

The key point of the model is simplification. Since the belt of the ECVT is elasticity, the ECVT is an infinite dimensional dynamical system, to be exact. Such dynamics are too complex for modern automotive embedded computers to calculate the inverse of system. Therefore, this paper simplifies the dynamics as follows;

1. The primary sheave position is forcibly determined by the electric motor of the ECVT. It is independent from belt tensions.
2. The secondary sheave position follows a second-order differential equation of motion of its sliding sheave.
3. The primary belt width and the secondary belt width are calculated from approximate first-order differential equations.
4. The rotational velocities of the primary sheave and the secondary sheave is derived from first-order differential equations of rotational motions.
5. Vibrations in a direction perpendicular to the belt move are assumed to be negligibly minimal.
6. The mass of the belt is approximated by zero.
7. Correlation between belt tensions and a belt slip velocity is described by using Gerbert's equation [6].
8. Tensions of the belt and compressional forces on the belt are associated with the experimental formulae of Worley and Miloiu [7, 8].
9. The transmission efficiency is computed from a belt slip velocity and a belt bend loss [9].

In this chapter, “the base state” of the ECVT means a state where the speed reduction ratio is lowest and the engine rotational velocity is zero. And, we use the SI units to define physical dimensions of physical quantities.

Mechanical Alignment

Let P_1 , R_1 , and W_1 denote the primary sheave position, the primary pitch radius, and the primary belt width, respectively (Fig. 4). They satisfy

$$P_1 = \bar{P}_1 + 2R_1 \tan \theta - W_1 \quad (1)$$

where $\bar{P}_1$ is an offset to set $P_1 = 0$ at the base state and θ is a half of the V-wedge angle.