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Study on CVT Ratio Tracking Controller

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Abstract

Based on the comparison of control effects of PID control and fuzzy control, this dissertation designed hybrid ratio tracking controller combining the advantages of both PID and fuzzy control. Using MATLAB/Simulink, simulation research of typical working conditions was made, such as start up, acceleration and ramp driving. The results showed that the controller has strong capacity of robust and decoupling and good dynamic response and high accuracy control of steady state, and good dynamic stability under the resistance of outside environment.

*Keywords:*Continuously Variable Transmission; Ratio Tracking Control; PID Control; Fuzzy Control

1. Introduction

Continuously variable transmission (CVT) can allow driver to simplify operations according to driver’s intention and vehicle driving conditions. Combining with electronic control technology, speed ratio can be changed continuously in accordance with control strategy, which could reduce the driver's labor intensity and eliminate shift shock. The engine and external load can achieve the best match, which could improve fuel economy and emission performance. So it’s an ideal way to drive a car [1,2].

According to driver’s intention and vehicle driving conditions, CVT speed ratio can be controlled to change continuously, which make vehicle movement and driving resistance achieve a sense of the best match. So speed ratio control system is the core control system of CVT [3].

CVT control has high nonlinear time varying characteristics and strong coupling between input and output. The control effect directly influences shift quality and transmission efficiency. Conventional PID control has a simple structure, strong robustness, etc., but the system model requires high accuracy and parameters setting is under a complete certain condition. When under actual and complex driving

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conditions, it's difficult to guarantee good control effect. Fuzzy control has good adaptability and decoupling effect to uncertainty and nonlinearity of system model, but it's difficult to ensure high control accuracy. Comparing the advantages and disadvantages of the two control methods, a hybrid-type ratio tracking controller was designed to meet special requirements and development of integrated control system.

2. Vehicle Mathematical Model with CVT

CVT power-train can be simplified to two systems with rotation inertia, which is shown in Fig.1. Main parameters are shown in Appendix A.1

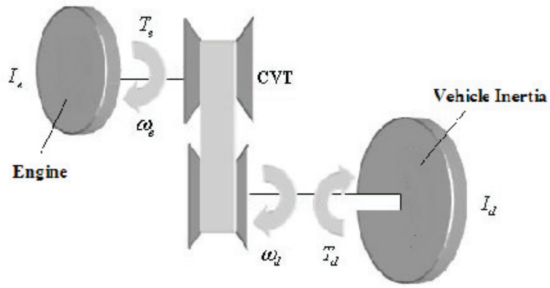

Fig.1 Power-train Model

The torque balance equation of input and output shaft of CVT is:

$$\left(T_e - I_e \cdot d\omega_e / dt\right) \cdot i \cdot \eta - T_d = I_d \cdot d\omega_d / dt \tag{1}$$

Where, T_e is engine output torque; T_d is equivalent moment of resistance from driving resistance to CVT output shaft; I_e is equivalent inertia from flywheel and driving pulley to input shaft; I_d is equivalent inertia from driven pulley and final drive to output shaft; ω_e is engine output shaft angular velocity; ω_d is CVT output shaft angular velocity; i is CVT speed ratio; η is transmission efficiency.

In the condition that there is no sliding between the belt and the pulley:

$$\dot{\omega}_e = di/dt \cdot \omega_d + \dot{\omega}_d \cdot i \tag{2}$$

Available from the torque balance equation:

$$\dot{\omega}_d = -di/dt \cdot \omega_e \cdot I_e / \left(I_e \cdot i^2 + I_d/\eta\right) + \left(T_e \cdot i^2 - T_d\right) / \left(I_e \cdot i^2 + I_d/\eta\right) \tag{3}$$

The above equations show that the change rate of ratio has a negative effect to vehicle acceleration, so, in order to ensure acceleration performance and driving comfort, CVT speed ratio should change moderately [4]. Vehicle dynamic model with a CVT system is shown in Fig. 2(a).

3. Ratio Tracking Controller Design

3.1. Ratio tracking control strategy

CVT ratio control is classified as two modes: power mode and economy mode, which can be chosen according to driver desire. When the driver depresses the accelerator pedal, the target engine speed and CVT speed ratio are set down. Therefore, we must design the target speed ratio with specific mode according to engine map data, to ensure that under different working conditions, the actual ratio can effectively track the target speed ratio, in order to achieve full engine power, improve vehicle dynamic performance and improve fuel economy and emission purpose[5-8].

3.2. Ratio tracking controller design

PID controller has the form as follows:

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau)\,d\tau + K_d\, de(t)/dt \tag{4}$$

Where, $u(t)$ is control variable, K_p is scale factor; K_i is integral factor; K_d is differential factor; $e(t)$ is error. The parameters of PID controller are shown in Appendix A.2.

The control output surface of fuzzy controller is shown in Fig.2 (b).

Using MATLAB/Simulink, a hybrid ratio tracking controller is designed. It consists of three parts: PID controller, fuzzy controller and PID/fuzzy control selector. PID/fuzzy control selector is the core part, which can judge real-time tracking by switching PID controller and fuzzy controller automatically. So it's designed to achieve a certain state: when there is large quantity of error, the ratio track is quick and smooth; when there is a small amount of error, ratio tracking has high accuracy.

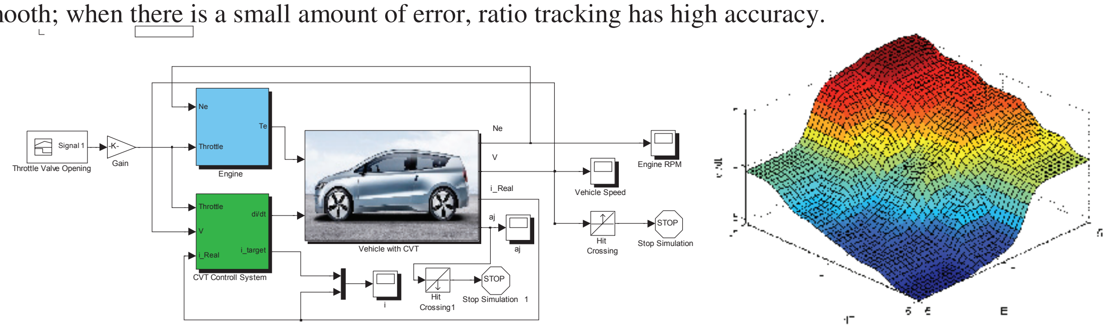

Fig.2 (a) Vehicle Dynamic Model Base on MATLAB/Simulink (b) Fuzzy Control Output Surface

4. Simulation Analysis

4.1. Start up condition

The engine throttle was opened from 8% to 40%, which lasted for 2 seconds, the simulation results were shown in Fig.3. In this process, the engine speed increased, meanwhile the maximum speed ratio was maintained, vehicle velocity increased. When the velocity reached 20km/h, the torque converter was locked, then the speed ratio continuously declined, and velocity continued to increase until the equilibrium with the driving resistance.

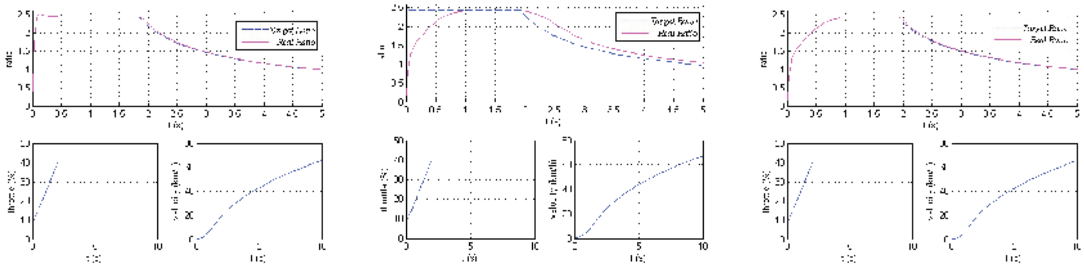

Fig.3 (a) PID Control (b) Fuzzy Control (c) Hybrid Control

4.2. Acceleration condition

The engine throttle was opened to 20% and the vehicle had a constant speed until 3 seconds later, throttle opening soared to 70%, when the operating mode changed from economy mode to power mode. The simulation results were shown in Fig.4. In this process, the speed ratio increased to the maximum and the vehicle velocity increased, but the engine was in non-steady-state. When the engine speed reached to the target value, the speed ratio was regulated to decrease until the equilibrium with the driving resistance.

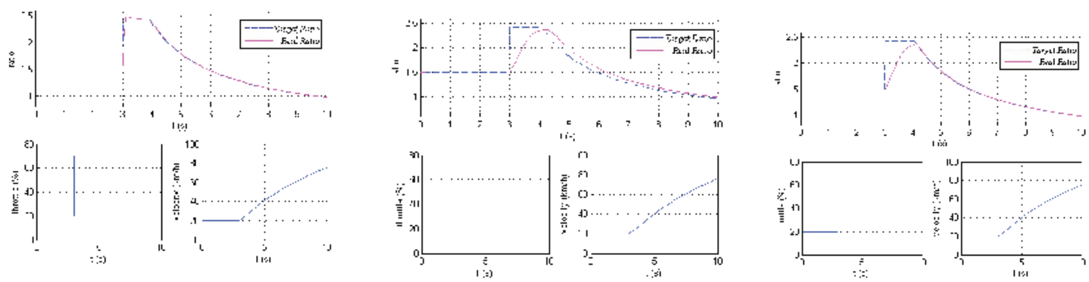

Fig.4 (a) PID Control (b) Fuzzy Control (c) Hybrid Control

4.3. Ramp driving condition

The engine throttle was opened to 60% and 5 seconds later, the vehicle encountered 5° slope resistance. The simulation results were shown in Fig.5. When the slope resistance occurred, the engine speed and the vehicle acceleration decreased, the change rate of speed ratio increased. When resistance disappeared, acceleration increased, the change rate of speed ratio decreased, the engine speed went back to the target value. The ratio tracking had good effect in this process.

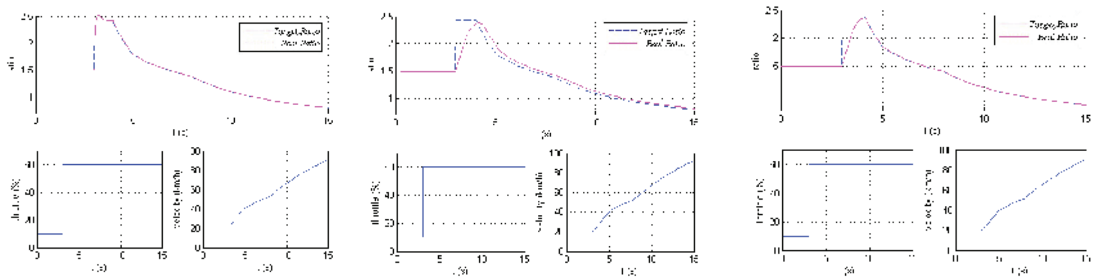

Fig.5 (a) PID Control (b) Fuzzy Control (c) Hybrid Control

The simulation results showed: When under PID control, ratio tracking had overshoot or rising too fast, but actual ratio delay was small with high precision in the later process; When under fuzzy control, ratio tracking had smooth characteristics, but the steady-state accuracy was not high; When under hybrid control, ratio tracking was smooth and steady, and delay was low and accuracy was high when the error is small. The engine was working at ideal points constantly. The results showed that the hybrid ratio tracking controller was effective.

5. Conclusion

In this dissertation, a hybrid ratio controller was designed based on PID and fuzzy control theory. The simulation under typical conditions showed that the closed-loop hybrid controller can achieve a good tracking performance and had strong robustness, good dynamic response, high steady-state control accuracy and dynamic stability under the resistance of outside environment.

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Appendix A.

A.1. Basic Parameters of the Vehicle Model

Parameter	Symbol	Unit	Value
Vehicle Mass	M	Kg	1560
Engine Max. Power	P_{emax}	Kw	56
Engine Max. Torque	T_{emax}	Nm	115
Engine Inertia	I_e	kg m^2	0.12
Frontal Area	A	m^2	1.68
Wind Resistance Coefficient	C_D		0.32
Rolling Resistance Coefficient	f		0.012
Wheel Rolling Radius	r_w	m	0.27
CVT Ratio Range	i_{CVT}		0.442~2.45
Final Drive Ratio	i_0		5.249

A.2. Parameters of PID Controller

Expression	K_p	K_i	K_d
$\lvert i_{target} - i_{real} \rvert \le i_1$	15	0.1 (if $\lvert di/dt \rvert > \Delta$) or 0 (if $\lvert di/dt \rvert \le \Delta$)	0.7
$i_1 < \lvert i_{target} - i_{real} \rvert \le i_2$	45	0.01	0.15
$\lvert i_{target} - i_{real} \rvert > i_2$	50	0.06	0

Where, i_1 *is* ratio lower threshold; i_2 *is* ratio upper threshold; i_{target} *is* target ratio; i_{real} *is r*eal ratio; Δ is the threshold of change rate of i_{real}.