Chapter 41
Study on Dynamic Torque PID Control for Automobile Diaphragm Spring Clutch Based on Kalman Filter

Chen Shao, Xue Bin Wu, Xin Zhang and Hong Wei Chen

Abstract This paper built a power transmission model based on Parallel Hybrid Electric Vehicle (PHEV). Based on this model, the Kalman filtering algorithm which was used to estimate the clutch transmitting torque was derived by the state vector which consist of the engine rotation torque and speed. The PID controller which was built based on the Kalman filtering was used to control the deviation between estimated torque and target torque. And the control errors are analyzed by comparing the controlled values and simulated values of the clutch torque at vehicle starting process by engine-driven. The conclusion show that the PID controller has the sufficient accuracy and response speed. Therefore, the PID controller of clutch transmitting torque are feasible.

Keywords PHEV · Diaphragm spring clutch · Kalman filtering · Torque · PID

41.1 Introduction

To improve the control performance and stability of automobile clutch during the switching process in Hybrid Electric Vehicle, the engine torque and clutch transmission torque must be coordinated. It is particularly important to control the engagement of automated clutch in the various driving cycle. But the clutch friction torque is immeasurable in the driving process. Clutch torque cannot be controlled directly in the process of PHEV mode switch. Many control methodologies of clutch engagement have been discussed through many research activities. Esenovsky-Lashkovy and Polyak [1] introduced a strategy aiming at controlling the throttle angle and the engine speed. The results show that the control strategy cannot satisfy driver's comfort. It is defective to set the engine information as single basis for clutch engagement law. Glielmo et al. [2] proposed the optimal methods

C. Shao (✉) · X.B. Wu · X. Zhang · H.W. Chen
School of Mechanical, Electronic and Control Engineering,
Beijing Jiaotong University, Beijing 100044, China
e-mail: 15121353@bjtu.edu.cn

Society of Automotive Engineers of China (SAE-China), *Proceedings of SAE-China Congress 2016: Selected Papers*, Lecture Notes in Electrical Engineering 418,
DOI 10.1007/978-981-10-3527-2_41

based upon the clutch release bearing position, engine speed and main-shaft speed on power transmission system model. The transmission load torque is transferred to the main shaft on this model which is assumed as rigid body.

In this paper, Kalman filter technology is applied to the clutch torque estimation. Based on dynamic analysis on the model of power transmission system, the transmission friction torque in the process of clutch engagement is estimated by Kalman filter. The discrete incremental PID controller of the friction torque is designed based on the control parameters which are made of the estimated torque and the specific torque, so that the clutch torque can be controlled placidly during clutch combination and separation.

41.2 PHEV Powertrain Model

The PHEV powertrain system includes the engine mode, motor model, battery model, clutch model, transmission model, main reducer, mechanical accessories and other electric components. The schematic diagram of coaxial parallel hybrid electric vehicle (PHEV) of powertrain system is shown in Fig. 41.1.

It is clear that the motor is arranged between the automatic clutch and the transmission in this system from Fig. 41.1. The parallel hybrid power system is very close to the traditional automobile power system in the structure, which is good in inheritance and easy to realize industrialization.

When the clutch is in separation/sliding, the powertrain system has two degrees of freedom. The engine is acted by engine torque and clutch transmission torque together. And the input shaft of AMT is acted by motor torque and clutch transmission torque. The dynamic equation is

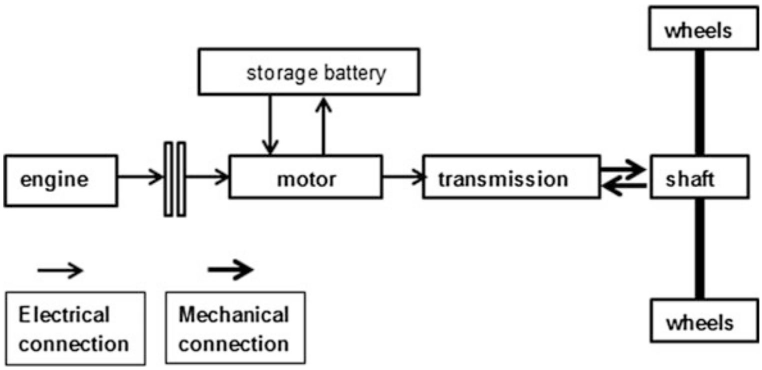

Fig. 41.1 Coaxial parallel hybrid system based on AMT

$$\begin{aligned} & J_e \dot{w}_e = T_e - T_c \\ & J_m \dot{w}_m + J_{veh} \dot{w}_{whl} / \left(i_g i_0 \right) = T_m + T_c - T_{load} / \left(i_g i_0 \right) \\ & \dot{w}_m = \dot{w}_{whl} \times i_g i_0 \end{aligned} \tag{41.1}$$

When the automatic clutch is in fully joint position, the powertrain system has only one degree of freedom. The clutch transmission torque turn into the internal force of the transmission shaft. The shaft is acted by the motor and the engine torque together. The dynamic equation is

$$\begin{aligned} & \left[J_e + J_m + J_{veh} / \left(i_g i_0 \right) \right] \dot{w}_m = T_m + T_e - T_{load} / \left(i_g i_0 \right) \\ & \dot{w}_m = \dot{w}_{whl} = \dot{w}_e \end{aligned} \tag{41.2}$$

$$J_{veh} = \frac{\mathrm{mr}^2 + \sum_{i=1}^{4} J_w(i)}{i_0^2 i_g^2} \tag{41.3}$$

where

J_e	is the rotation inertia of the engine
J_m	is the rotation inertia of the engine
J_{veh}	is equivalent to the transmission shaft rotation inertia
w_e	is the engine angular velocity
w_m	is the motor angular velocity
w_{whl}	is equivalent to the transmission shaft angular velocity
T_e	is the engine torque
T_m	is the motor torque
T_{load}	is equivalent to the transmission shaft resistance torque
i_g	is current gear transmission ratio of gearbox
i_0	is main speed reducer's ratio
m	is the mass
r	is the tire rolling radius
J_w	is the rotation inertia of the tire

By ignoring the effects of wind speed and driving wheel slip, T_{load} can be calculated as follows:

$$T_{load} = \frac{\mathrm{r}\eta}{i_0 i_g} [mg(f + i) + \frac{C_{\mathrm{d}} A}{1.632} (\frac{w_{whl} \times r}{i_0 i_g})^2] \tag{41.4}$$

where: f is rolling resistance factor, I is road slope, A is the windward area, C_d is the wind resistance coefficient.

By Eqs. (41.1), (41.2), (41.3), (41.4), the complete equations of power transmission system can be established. The vehicle parameters are shown in Table 41.1

Table 41.1 Vehicle parameters

Parameters	Value	Units
m (vehicle equipment quality)	15,500	kg
r	0.4643	m
A	6.73	m^2
C_d	0.65	
J_e	0.3	kg m^2
J_m	0.2	kg m^2
f	0.015	
i_0	6.17	
i_g	3.71	
η	0,.85	
J_w	1.1	kg m^2
i	0.018	rad

41.3 Clutch Torque Estimation Model Based on Kalman Filter Arithmetic

The being measured data is taken as the estimator in the soft sensing method based on the state estimation. The principle and application of this method are simple and the measured data can be estimated accurately as long as the measured object's mathematical model can be reflected precisely. In this paper, Kalman filter technology is based on state estimation.

41.3.1 System State Space Model

Based on the model of vehicle power transmission system, the Kalman filter estimator is used to estimate the transmission torque of the clutch, which is obtained by measuring the angular velocity of the engine and the torque of the engine.

The state space model for Kalman filtering is as follows

$$x_{k+1} = Ax_k + Bu_k \tag{41.5}$$

$$Y = Cx_k \tag{41.6}$$

The state variable in the equation is

$$x_k = \begin{bmatrix} \omega_e(k+1) \\ \omega_e(k) \\ T_c(k+1) \\ T_c(k) \end{bmatrix} \tag{41.7}$$

The control input variable u_k is

$$u_k = \begin{bmatrix} T_e(k+1) \\ T_e(k) \end{bmatrix} \tag{41.8}$$

The measurement output variable Y is

$$Y = [\omega_e(k)] \tag{41.9}$$

where

ω_e is the engine speed
T_c is the Clutch transmission torque
T_e is the engine torque

41.3.2 State Space Model Parameter

After state space model is derived, the parameters that are used in the program of Kalman filter estimation algorithm need be calculated. Dynamic transmission equation can be written as

$$T_e - T_c = j_e \dot{\omega} \tag{41.10}$$

$$\dot{T}_e - \dot{T}_c = j_e \ddot{\omega} \tag{41.11}$$

The discrete equation is

$$\omega_e(k) = \frac{\Delta T}{J_e}[T_e(k) - T_c(k)] + \omega_e(k-1) \tag{41.12}$$

$$\omega_e(k+1) = \frac{\Delta T}{J_e}[T_e(k+1) - T_c(k+1)] + \omega_e(k) \tag{41.13}$$

$$\begin{aligned} T_c(k+1) &= T_e(k+1) - T_e(k) + T_c(k) \\ &- \tfrac{J_e}{\Delta T}[\omega_e(k+1) - 2\omega_e(k) + \omega_e(k-1)] \end{aligned} \tag{41.14}$$

$$x_{k+1} = A_1 x_{k+1} + A_2 x_k + B_1 x_k \tag{41.15}$$

$$Y = C x_k \tag{41.16}$$

The coefficient matrix is

$$A_1 = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ \frac{J_e}{\Delta T} & -\frac{J_e}{\Delta T} & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \qquad C = \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

$$A_2 = \begin{bmatrix} 0 & 1 & -\frac{\Delta T}{J_e} & 0 \\ 0 & 0 & 0 & -\frac{\Delta T}{J_e} \\ -\frac{J_e}{\Delta T} & \frac{J_e}{\Delta T} & 0 & 1 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad B_1 = \begin{bmatrix} \frac{\Delta T}{J_e} & 0 \\ 0 & \frac{\Delta T}{J_e} \\ 1 & -1 \\ 0 & 0 \end{bmatrix}$$

The coefficient matrix is

$$\begin{aligned} A &= [I - A_1]^{-1} A_2 \\ B &= [I - A_1]^{-1} B_1 \end{aligned} \tag{41.17}$$

The system state space model has been established based on the above equation.

41.3.3 The Simulink Model Based on Kalman Filter

The classical Kalman filter algorithm equation is

$$\begin{cases} \textit{time-update-equation} \begin{cases} \hat{x}_{k/k-1} = \varphi_{k,k-1}\hat{x}_{k-1} \\ \hat{P}_{k/k-1} = \varphi_{k,k-1}\hat{P}_{k-1}\varphi_{k,k-1}^T + Q_{k-1} \end{cases} \\ \textit{status-update-equation} \begin{cases} K_k = P_{k/k-1}H_k^T/[H_k P_{k/k-1} H_k^T + R_k] \\ \hat{x}_k = \hat{x}_{k/k-1} + K_k\left[Z_k - H_k\hat{x}_{k/k-1}\right] \\ P_k = [I - K_k H_k]P_{k/k-1} \end{cases} \end{cases} \tag{41.18}$$

where:

$\hat{x}_{k/k-1}$ is state of the predicted from the moment k − 1 to k;
$\hat{x}_k$ is state of the estimated value in the moment of k;
K_k is the filter gain matrix on in the moment of k;
$\hat{P}_{k/k-1}$ is the covariance matrix of predicted error from the moment k − 1 to k;
P_k is the covariance of estimated error in the moment of k;
Q_{k-1} is the covariance matrix of systematic noise;
R_k is the measurement noise covariance.

The clutch transmission torque program is written in the Matlab. And the Simulink model is established based on the Kalman filter to estimate the clutch transmission torque at the start process of the engine (Fig. 41.2).

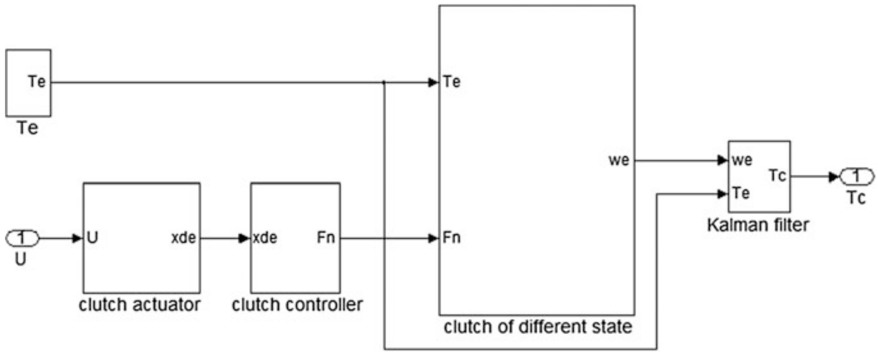

Fig. 41.2 The Simulink model of torque estimation

41.4 PID Controller for Clutch Torque

The PID controller can control the deviation between estimation value and target value of the clutch torque in real time, so that the optimal clutch control can be obtained.

41.4.1 PID Controller Design

PID controller is a linear controller and its control input is the deviation between target value and actual value. The equation is

$$e(t) = r(t) - c(t) \tag{41.19}$$

Clutch torque follow PID control law can be expressed as:

$$u(k) = k_p e(k) + k_i \sum_{j=0}^{k} e(j)T + k_d \frac{e(k) - e(k-1)}{T} \tag{41.20}$$

where

e(k) is engine torque deviation; K_p is PID ratio coefficient; K_i is PID integral coefficient; K_d is PID differential coefficient; u(k) is PID output; T is sampling period. Under the Simulink environment, the PID control model of power transmission system is set up on the condition of starting process driven by engine (Fig. 41.3).

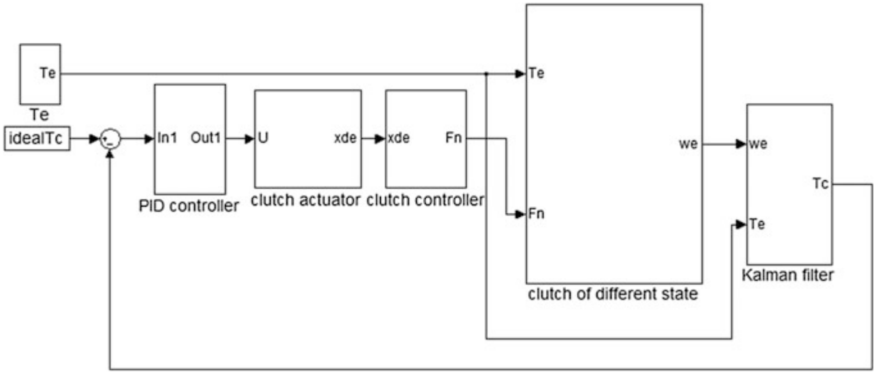

Fig. 41.3 The torque estimation Simulink model of system PID controller

Table 41.2 Regulator experience data sheet for critical proportion method

Regulating law	P (%)	T_I	T_D
P	2 P_m		
PI	2.2 P_m	0.85 T_m	
PID	1.7 P_m	0.5 T_m	0.13 T_m

P_m and T_m can be calculated by the pure proportion
$P_m = 2.432335$, $T_m = 1.3$ ms

41.4.2 Parameters Setting and Analysis of PID Controller

The process of determining the proportional, integral and differential coefficient is called parameters setting of PID controller. The three parameters are closely related to the control effect of the controlled system, which determine the quality of the controlled object.

The critical proportion method (also known as the stability boundary method) is used in the paper. The regulating law is to increase the proportion coefficient ceaselessly based on the pure proportion, and then make the controlled parameter of the system being the steady boundary. And each coefficient can be calculated according to the empirical data of Table 41.2 after measuring the ratio of the amplification factor K_m or the critical ratio P_m and the oscillation period T_m.

And the sampling period of PID is 1 ms. K_i and K_d can be calculated as follows:

$$K_{\rm i} = K_p \frac{T}{T_i} \qquad K_{\rm d} = K_p \frac{T_{\rm d}}{T} \tag{41.21}$$

$K_i = 6.3615$, $K_d = 0.7$

The PID control effect is shown in Fig. 41.4a.

It can be seen from the figure that the system static error has been eliminated, but the overshoot is larger, and the response time is long, so the PID parameters should be further adjusted on the basis of the above. Finally, the optimal parameters are as

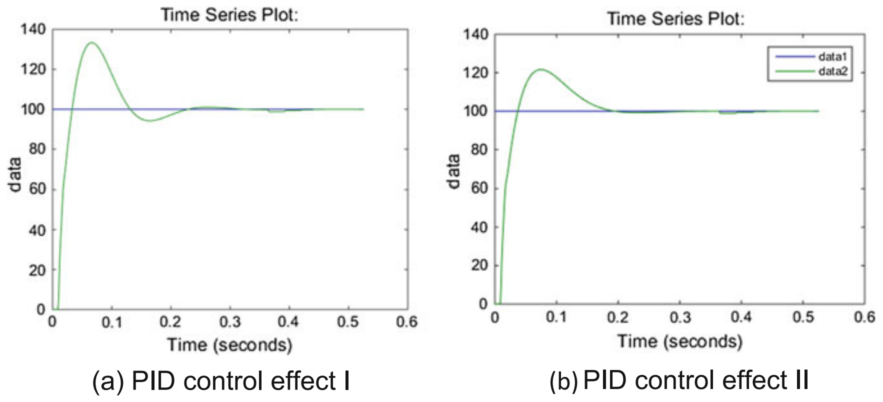

Fig. 41.4 PID control setting

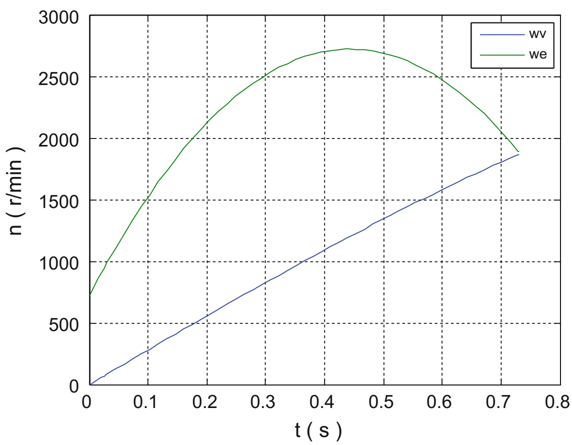

Fig. 41.5 Clutch speed simulation at starting process

follows: $K_p = 5.324$, $K_i = 2241$, $K_d = 0.86$. The PID control effect is shown in Fig. 41.4b.

It can be seen that the PID control error is very small, and the dynamic response speed is relatively fast, so the design of the PID controller can meet the requirements.

41.5 PID Control Simulation and Analysis of Clutch Torque at Starting Process Driven by Engine

Engine torque and DC motor voltage are given: $T_e = 200$ Nm, U = 24 V. The figure of the engine speed and the wheel speed at starting process is shown. Where we is engine speed and wv is clutch speed in Fig. 41.5.

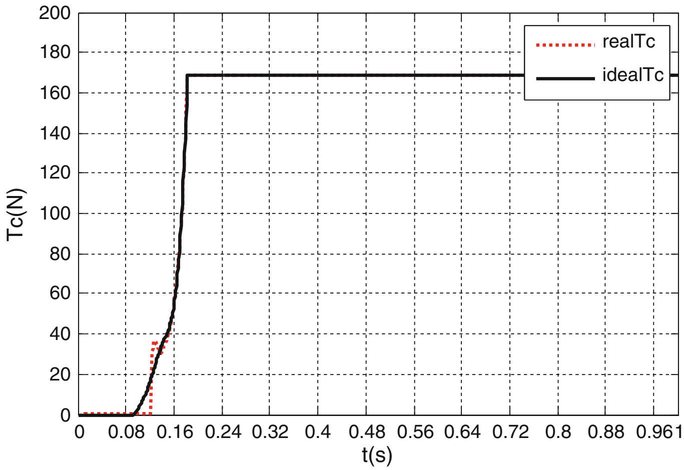

Fig. 41.6 Clutch simulation by PID at starting process

The coefficient of PID can be obtained through the above PID setting process as follows:

$$K_p = 5.324, \quad K_I = 2241, \quad K_D = 0.86$$

According to the established PID control system above, the clutch torque is simulated at starting process driven by engine (Fig. 41.6).

41.6 Conclusion

A parallel hybrid electric vehicles is taken as the research object and the model of powertrain system with automatic clutch is built in this paper.

The discrete state equations and the observation equations for torque estimation of clutch are derived on the starting condition driven by engine. Clutch transmission torque estimation method is designed based on discrete Kalman filter. The estimation value and the target value are taken as two parameters. The PID clutch torque following controller is designed to control the transmission torque of the automatic diaphragm spring clutch in real time.

Through the analysis above, the deviation of Kalman filter estimation is relatively small. And the PID controller can meet the requirements of the torque tracking accuracy and response speed. It can be applied to the control of automatic clutch transmission torque, which can realize the stability of the control performance during the lifetime of the clutch and improve the quality of the switching process of the HEV mode.

References

1. Esenovsky-Lashkov Y, Polyak D (1996) New concept of automatic control for a passenger car clutch. Proc Inst Mech Eng Part D J Automobile Eng 210(3):227–233
2. Glielmo L, Iannelli L, Vacca V, Vasca F (2006) Gearshift control for automated manual transmissions. IEEE/ASME Trans Mechatron 11(1):17–26