Integrated Control Optimization of Dual Clutch Transmission Gears for Electric Vehicles

Jiawei Sheng\textsuperscript{a}, Jinyue Tian\textsuperscript{b}, Yihui Gu\textsuperscript{c} and Yongtong Jia\textsuperscript{d}

School of Automotive and Traffic Engineering, University of Jiangsu, Zhenjiang, Jiangsu 212013, China

\textsuperscript{a}280260847@qq.com, \textsuperscript{b}411806937@qq.com, \textsuperscript{c}1024506199@qq.com, \textsuperscript{d}316536781@qq.com

Abstract. The control of the transmission shift in vehicles is significant for driving comfort. In order to analyze the shift quality effectively, the transmission system dynamic parameters are taken as the input variables, and the comprehensive evaluation index of the weighted form of the jerk and friction work is introduced to determine the optimization objective function. The optimization problem of dynamic parameter input variables is transformed into the parameter optimization problem that particle swarm can be processed by Fourier transform. So the optimal torque trajectory of the motor and clutch during the upshift is obtained.

1. Introduction

The dual clutch transmission retains many advantages of the manual transmission, such as compact structure, small mass, high transmission efficiency and so on. In addition, it also has the advantages of good quality of the AT and CVT, with good shift quality, vehicle dynamics and economy. This paper analyzes the electric drive system equipped with two speed dry DCT. The separation and combination process of the dual clutch is reasonably controlled based on the particle swarm optimization algorithm to minimize the jerk and friction work during the shifting process.

2. Optimized objective function

In the shifting process of the clutch transmission, the jerk and sliding work must be effectively controlled to ensure the smoothness and comfort of the shifting of the vehicle and the service life of the dual clutch. The clutch engagement time is short, that is, the driven disc speed reaches the driving disc speed quickly, which means the slipping time of clutch is short and the friction work is small. However, in this case, the jerk will increase and the shifting smoothness and comfort will be reduced. Jerk and friction work are two basic indicators of mutual restraint [1, 2]. Therefore, it is necessary to carry out reasonable shifting process dynamic control so that both indicators can achieve satisfactory results. The two indicators are weighted to develop a comprehensive shift quality evaluation index [3].

\[ J = \lambda_1 \cdot W + \lambda_2 \cdot \sum_{i=0}^t j^2(i) \] (1)
Where, $\lambda_1$ ---weighting coefficient for friction work, $\lambda_1 > 0$; $\lambda_2$ ---Weighting coefficient for jerk, $\lambda_2 > 0, \lambda_1 + \lambda_2 = 1$; $W$ ---Friction work; $j(t)$ ---Jerk. Since the jerk has positive and negative values, the square sum form is used in the equation.

The comprehensive evaluation index $\lambda_1$, $\lambda_2$ use the weight coefficient, taking into account both the jerk and friction work. By adjusting the weight $\lambda_1$, $\lambda_2$, it can match requirements of jerk and friction work in practical applications. It can be seen from Eq.1 that the comprehensive evaluation index is based on jerk and friction work and has objectivity. At the same time, it not only considers the smoothness of the shifting process, but also takes into account the service life of the dual clutch, which is comprehensive [4].

According to the dynamic relationship analysis, the shifting jerk and friction work in the torque phase can be expressed as:

$$j_1(t) = \frac{i_0}{\delta m_{rw}}\left[ \frac{d \tau_{m1}(t)}{dt} + (i_1 - i_2) \frac{d \tau_{c2}(t)}{dt} \right]$$

$$W_1 = \int_{t_0}^{t_1} T_{c2} |\omega_m - \omega_{c2}| dt$$

Where, $i_0$ --- main reducing gear ratio; $i_1$ ---DCT first gear ratio; $i_2$ ---DCT second gear ratio;

The shifting jerk and friction work in the inertia phase can be expressed as:

$$j_2(t) = \frac{i_0 i_2}{\delta m_{rw}} \frac{d \tau_{c2}(t)}{dt}$$

$$W_2 = \int_{t_1}^{t_2} T_{c2} |\omega_m - \omega_{c2}| dt$$

According to the Eq.1, the objective function of the particle swarm optimization algorithm for the positive torque upshift process and the inertia phase is obtained.

$$J_1_{\text{min}} = \lambda_1 \cdot W_1 + \lambda_2 \cdot \sum_{i=0}^{t_1} j_1^2(t)$$

$$J_2_{\text{min}} = \lambda_1 \cdot W_2 + \lambda_2 \cdot \sum_{i=t_1}^{t_2} j_2^2(t)$$

In order to optimize the objective functions of Eq.6 and Eq.7, it is necessary to properly control the motor output torque and the clutch transmission torques to optimize the overall shift quality of the torque phase and the inertia phase.

3. Target torque optimization process based on PSO algorithm

The fitness indicates the pros and cons of each particle’s own location and search performance. When the algorithm terminates, the best fit particle is the searched optimal solution. The fitness function of this paper should be formulated according to the comprehensive evaluation indicators formulated above, that is, the minimum value of the comprehensive evaluation index during the shifting process. However, the particle swarm optimization algorithm is usually used to solve the parameter optimization, and cannot optimize the time trajectory of the motor output torque $T_m$ and the two clutch output torque $T_{c1}$, $T_{c2}$. Therefore, a reasonable equivalent transformation of the target torque is needed, which is transformed into a form that the particle swarm algorithm can handle [5, 6].

In order to ensure the reliability of the calculation, the first 24 Fourier basis functions are used to perform Fourier series decomposition on the optimization target. Drive motor output torque $T_m$ is decomposed into:
Where: $\alpha_0, \ldots, \alpha_{23}$ —— Fourier basis function coefficient of motor torque.

The clutches C1 and C2 transmit torque are decomposed into:

\[ T_{c1} = \beta_0 f_0(t) + \beta_1 f_1(t) + \ldots + \beta_{23} f_{23}(t) = \sum_{n=0}^{23} \beta_n f_n(t) \]  
\[ T_{c2} = \gamma_0 f_0(t) + \gamma_1 f_1(t) + \ldots + \gamma_{23} f_{23}(t) = \sum_{n=0}^{23} \gamma_n f_n(t) \]

Where: $\beta_0, \ldots, \beta_{23}$ —— Fourier basis function coefficient of clutch C1

$\gamma_0, \ldots, \gamma_{23}$ —— Fourier basis function coefficient of clutch C2

By substituting Eq.8~Eq.10 into the optimization objective function Eq.6 and Eq.7 of the torque phase and inertia phase, the fitness function of the particle swarm optimization algorithm for positive torque upshift process can be obtained.

4. Results and analysis

According to the analysis of the shifting dynamics of the positive torque upshift process, the optimization calculation is performed on the determined particle fitness function. Assume that the number of particles is 24, the particle position $x_i$ is

\[ x_i = [\alpha_0^i, \alpha_1^i, \ldots, \alpha_{23}^i, \beta_0^i, \beta_1^i, \ldots, \beta_{23}^i, \gamma_0^i, \gamma_1^i, \ldots, \gamma_{23}^i]^T \]

The maximum number of iterations is 2000.

When the accelerator pedal opening is 15% and the vehicle is running at 15km/h, the torque phase and the inertia phase particle position change during the positive torque upshift process are as shown in Fig.1 and Fig.2. At this time, the weight of the jerk is $\lambda_1=0.4$ and the weight of the friction work is $\lambda_2=0.6$.

\[ T_m = \alpha_0 f_0(t) + \alpha_1 f_1(t) + \ldots + \alpha_{23} f_{23}(t) = \sum_{n=0}^{23} \alpha_n f_n(t) \]

\[ T_{c1} = \beta_0 f_0(t) + \beta_1 f_1(t) + \ldots + \beta_{23} f_{23}(t) = \sum_{n=0}^{23} \beta_n f_n(t) \]

\[ T_{c2} = \gamma_0 f_0(t) + \gamma_1 f_1(t) + \ldots + \gamma_{23} f_{23}(t) = \sum_{n=0}^{23} \gamma_n f_n(t) \]
individual remembers in the process of finding the best, and indicates the best position of the individual's fitness.

It can be seen that the particles are continuously updated by the information sharing throughout the search process. Finally, it gathers to the optimal position of the group, that is, the optimal value of the objective function.

The optimum values of the particle swarm algorithm in the torque phase and inertia phase during the positive torque upshift process are shown in Fig.3 and Fig.4.

![Figure 3. Optimal value change in torque phase.](image1)

![Figure 4. Optimal value change in inertial phase.](image2)

Although the adaptation value of the population initialization scheme is very poor, the population's fitness value decreases rapidly because the population can obtain information from each particle. At about 50 generations, the information interaction between the particles in the population enters a slow phase, and most of the particles fly near the optimal position until all particles find the optimal solution. The results of the torque phase and inertia phase optimization are shown in Table 1.
Table 1. Optimization results of torque phase and inertia phase in positive torque upshift.

| Number of iterations | Zbest                          | Optimal value of the objective function |
|----------------------|--------------------------------|------------------------------------------|
| Torque phase         |                                |                                          |
| 500                  | (35.1, 273.9,..., 25.6, 273.6, 32.7) | 68.357                                   |
| 1500                 | (17.1, 13.4,..., 324.3, 117.9, 4.7)  | 55.289                                   |
| 2000                 | (17.1, 13.4,..., 324.3, 117.9, 4.7)  | 55.289                                   |
| Inertial phase       |                                |                                          |
| 500                  | (313.4, 54.2,..., 98.3, 83.4, 65.2)   | 73.785                                   |
| 1000                 | (29.6, 45, 2,..., 32.1, 23.5, 40.3)   | 67.919                                   |
| 1500                 | (29.6, 45, 2,..., 32.1, 23.5, 40.3)   | 67.919                                   |

Note: Zbest represents the position of the optimal particle.

As can be seen from Table 1, the optimal phase position Zbest is constantly changing as the number of iterations increases. After 1500 iterations, Zbest no longer changes. The best results have been obtained, and the optimal value of the objective function is 55.289. After 1000 iterations in the inertia phase, the optimal particle position Zbest has remained basically unchanged, and the optimal value of the objective function is 67.919.

By substituting each element $\alpha_i$, $\gamma_i$, $\beta_{2i}$, $\beta_{2i}$, $\gamma_{2i}$, $\gamma_{2i}$ in the optimal result into Eq.9–Eq.11, the optimal trajectory of motor torque and clutch C1 and C2 torque during positive torque upshift can be obtained as shown in Fig. 5. The jerk and friction work of the system are shown in Fig. 6 and Fig. 7.
It can be seen from Fig.6 that after the particle group optimization algorithm is used to optimize the torque transmitted during the positive torque upshift process, the jerk of the system during the shifting process is controlled at 5.2 m/s³, which is reduced compared with the jerk 6.94 m/s³ before optimization.

The friction work during the entire shifting process is 6.5 KJ, which is 7.4% lower than the 7.02 KJ before optimization in the Fig.7.

5. Conclusion
Through the dynamic relationship between the components during the positive torque upshift process, the reasonable constraints are added to the optimization process. The motor and clutch transmission torques are used as input variables for optimization calculation during the shifting process. The calculation results show that the jerk and friction work index are reduced compared with those before optimization, which improves the shift quality. The particle swarm optimization algorithm optimizes the motor output torque and clutch transmission torque during the shifting process, so that the shift shock is reduced to less than 6 m/s³, and the friction work during the shifting process is reduced by 7.4% compared with the optimization.

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