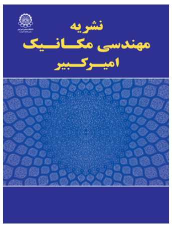

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Optimal cooperative braking strategy design of regenerative and mechanical braking systems for in-wheel drive electric vehicles

A. Hosseini Salari, H. Mirzaeinejad*, M. Fooladi Mahani

Department of Mechanical Engineering, Shahid Bahonar University of Kerman, Kerman, Iran

ABSTRACT: Nowadays, a new generation of electric vehicles with in-wheel motor technology has been introduced and is being developed. Increasing system efficiency, eliminating mechanical intermediaries, and achieving regenerative braking torque with better performance are the motivations to seek to improve this technology. In the present study, a half-car model with five degrees of freedom has been developed by considering a vehicle equipped with two in-wheel motors on the rear axle as a sample vehicle. Then, the braking strategy has been designed using a two-stage nonlinear predictive controller. The appropriate pressure for the brake fluid lines will be reached in the first stage. In the second stage, the proper amount of electric regenerative torque is obtained using the electronic braking force distribution function and considering all constraints. The amount of regenerative torque is calculated by considering the system constraints using the Karush–Kuhn–Tucker conditions. Finally, the designed strategy is examined from the perspective of vehicle mileage capability. The results show that optimal braking can be achieved by utilizing the designed controller and the proposed model. Also, the amount of regenerated energy to the battery can be increased during braking by using the proposed braking strategy and the designed control system in comparison with the relevant studies.

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1- Introduction

The maximum braking power to create the safest possible state is when the brake torque control systems use the maximum adhesion capacity between the tire and the road. To use the maximum tire and road capacity in braking mode, different controllers have been designed [1-5]. However, a complete explanation about the amount of torque requested by the driver has not been given, or possible modeling with many assumptions and uncertainties has been used. Or, many factors affecting the permissible amount of regenerative torque, such as the condition of the battery and standard limits, have been ignored. Another study used the PSO method to solve the energy equation in the predictive controller, and due to the nature of this solution method, it seems difficult to implement such a method industrially [6].

2- Modeling

In each state of transfer, change, transformation, and division of energy from battery to vehicle movement, a part of the energy is lost. In electric vehicles with in-wheel-motor propulsion, many of these interface elements and energy converters are eliminated. To check the energy consumption in cars equipped with in-wheel motors, the resistance forces of the car are modeled as follows:

$$F_a = \frac{1}{2}\rho c_d A_f v_x^2 \tag{1}$$

$$F_{Ri} = f_R F_{zi} \quad i = f,r \tag{2}$$

Also, the sum of the incoming forces in the longitudinal direction of the car is as follows [6]:

$$F_x = 2(F_{tf} + F_{tr} - F_{Rf} - F_{Rr}) - F_a \tag{3}$$

To model the energy cycle in an electric vehicle and model the tire and road contact surface as well as calculate the amount of energy loss in the contact surface, the following modeling is done. The amount of power at the head of each wheel is equal to:

$$P_{wi} = T_i \omega_i \quad i = f,r \tag{4}$$

In the braking mode, the total mechanical power is equal to the braking torque. Also, the power created by the tire for longitudinal movement is equal to:

$$P_{ti} = v_x F_{ti} \quad i = f,r \tag{5}$$

Longitudinal force is caused by the interaction of each tire with the road surface. According to the provided relationships,

*Corresponding author's email: h_mirzaeinejad@uk.ac.ir

the transaction efficiency of each tire surface with the road is defined as follows:

$$\eta_{Ti} = P_{ti} / P_{wi} \quad i = f,r \tag{6}$$

The total power regenerated and added to the battery is as follows:

$$P_R = \Sigma \zeta \eta_R P_{bi} \quad i = f,r \tag{7}$$

Where regenerative braking is the share of the total braking energy, which is determined by the braking strategy. Since the electric motors are placed only in the rear axle of the vehicle in question, the electric regenerative braking and its efficiency are defined only for the rear axle:

$$\eta_R = \eta_{Ch} \eta_{MC} \eta_M \eta_{Tr} \tag{8}$$

The motor efficiency relationship is based on the structure of the motor as follows:

$$\eta_M = \frac{T_E \omega_E}{k_c T_E^2 + T_E \omega_E + k_i T_E + k_w \omega_E^3 + cl} \tag{9}$$

It is the nominal capacity of each cell and the number of parallel cells in the battery pack and the voltage level of the battery pack. By charging the battery at the calculated current rate, the battery's level of charge (SOC) changes. In the simplest battery and charge level modeling, the amount of battery charge level changes over time is as follows:

$$SOC(t+\tau) = SOC(t) + \frac{\tau}{3600} \frac{T_E(t) \omega_r(t) \eta_R}{C_{cell} \, P_B S_B V_n} \tag{10}$$

Achieving the maximum possible braking acceleration depends on the accuracy of modeling, the type of brake torque controller, and its implementation. The selected model, 5DOF, includes all the dynamics affecting braking on a straight road. When the tire is rolling, rolling resistance forces, driving force, braking force, and starting torque or braking torque are applied to the tire. Since braking mode is discussed in this article, modeling is done in braking mode.

The state space for the mentioned model would be:

$$SOC(t+\tau) = SOC(t) + \frac{\tau}{3600} \frac{T_E(t) \omega_r(t) \eta_R}{C_{cell} \, P_B S_B V_n} \tag{11}$$

$$\dot{x}_2 = f_2(\boldsymbol{X}) + \frac{R}{x_1 I_{wf}} C_{pf} u_1 \tag{12}$$

$$\dot{x}_3 = f_3(\boldsymbol{X}) + \frac{R}{x_1 I_{wr}} \left[C_{pr} u_2 + u_3 + T_{Es} \right] \tag{13}$$

$$\dot{x}_4 = f_4(\boldsymbol{X}) \tag{14}$$

$$\dot{x}_5 = f_5(\boldsymbol{X}) \tag{15}$$

While $\boldsymbol{X} = [x_1, x_2, x_3, x_4, x_5]^T = [v_x, \lambda_f, \lambda_r, \theta, \dot{\theta}]^T$ and $\boldsymbol{U} = [u_1, u_2, u_3]^T = [P_{of}, P_{or}, T_{Ed}]^T$. The f_i are as follows:

$$f_1 = F_x(x_1, x_2, x_3, x_4) / m, \tag{16}$$

$$f_2 = \frac{-1}{x_1} \left[\frac{F_x}{m} (1 - x_2) + \frac{R^2 F_{tf}}{I_{wf}} \right] \tag{17}$$

$$f_3 = \frac{-1}{x_1} \left[\frac{F_x}{m} (1 - x_3) + \frac{R^2 F_{tr}}{I_{wr}} \right] \tag{18}$$

$$f_4 = x_5 \tag{19}$$

$$f_5 = \frac{1}{I_y} \left[\frac{1}{2} m_s h_s x_1 - l_f F_{sf} + l_r F_{sr} \right] \tag{20}$$

3- Control design

In this article, the predictive nonlinear control method will be used to design the control system. The basis of this method is that the nonlinear response of the system in a later period of time is predicted by Taylor series expansion, and then the control law is found at the current moment so that the predicted tracking error is minimized. Hence the $P_{of}(t)$ can be obtained as a function of the control input:

$$J_1(P_{of}) = \frac{1}{2} \left[\frac{C_{pf} R h}{v_x I_{wf}} P_{of} + \left(h f_2 + e_{\lambda_f} - h \dot{\lambda}_{fd} \right) \right]^2 \tag{21}$$

So that the tracking error $e_{\lambda_f} = \lambda_f - \lambda_{fd}$ is longitudinal slip. Then it is calculated by applying the necessary condition for the optimum oil pressure.

$$P_{of} = -\frac{I_{wf} v_x}{C_{pf} R h} \left(e_{\lambda_f} + h f_2 - h \dot{\lambda}_{fd} \right) \tag{22}$$

In this article, taking into account the default mode of active EBD, the normal pressure of the rear lines reaches the minimum possible value ($P_{or} = \Gamma^* P_o$) and the slip control action is assigned to the regenerative electric torque. Electric braking torque controller, taking into consideration the momentary conditions of the road, the tire, and the vertical load on the tire, creates the right torque and controls the slip at the optimal point. The electric braking torque is determined in such a way that the electric torque controller takes over the skid control operation at the same time as the optimal oil pressure of the rear wheels decreases. Therefore, the energy function of the controller of the second stage will be as follows:

$$J_2\left(T_{Ed}\right)=\frac{1}{2}w_1\left[\lambda_r\left(t+h\right)-\lambda_{rd}\left(t+h\right)\right]^2 +\frac{1}{2}w_2\left[T_{Ed}-\kappa T_{Dp}\right]^2,\quad \kappa=\frac{D_p^*-D_p}{D_p^*} \tag{23}$$

Finally the control law would be like below while the vehicle constrains act as boundaries for this value

$$T_{Ed}=\frac{\left[w_2\kappa T_{Dp}-w_1\left[\frac{R^2h^2}{{v_x}^2I_{wr}^2}C_{pr}\Gamma^*P_o+\frac{Rh}{v_xI_{wr}}\left(e_{\lambda_r}+h\left(f_3-\dot{\lambda}_{rd}\right)\right)\right]\right]}{w_2+w_1\frac{R^2h^2}{{v_x}^2I_{wr}^2}} \tag{24}$$

As mentioned, Γ^* it is calculated based on the maximum capacity of EBD compensation and electric braking torque generation. Since the above constraints and limiters may limit the amount of optimal electric braking torque, the amount sent to the hydraulic module to reduce the pressure of the rear axle lines is calculated as follows:

$$\Gamma^{**}=\Gamma^*(P_oC_{pr}-T_{Ed}^{**})/P_oC_{pr} \tag{25}$$

4- Results

The study [7] has reached the maximum improvement percentage of 22% by considering standard parameters, safety, and limitations. Meanwhile, the performance of the proposed method in this article shows a 24% improvement in navigation. In reference [5], like this article, to check the performance of the proposed algorithm, the NEDC standard cycle is simulated. The results of applying the proposed strategy of this authority show a 21.1% improvement in energy consumption and navigation.

5- Conclusion

In this article, with the aim of designing a braking strategy for an electric vehicle equipped with motor-in-wheel technology, the 5DOF model and the electric energy cycle in the said vehicle were first explained. In the energy function, the potential compensable capacity of EBD was assigned to regenerative braking. The results of applying the designed strategy and controller in the standard navigation cycle show the improvement of the energy consumption situation in the car compared to previous studies.

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