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Control Strategy for Hill Starting of Electric Vehicle

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Abstract: In order to solve the problem of easy slipping on hill during the starting process of electric vehicle, the hill starting control strategy was established on the basis of hill-start assist system. The state equation of the slope recognition was achieved by simplifying the vehicle longitudinal dynamics equation and then a Luenberger observer was designed based on this state equation to recognize the road slope online. The problem of function trigger and the Hill Starting Aid valve control in the hill-start assist system had been solved by the slope recognition and starting resistance calculation. The simulation results show that the designed observer could recognize the road slope effectively and the system could meet the requirements of safety and driving comfort in hill starting process.

Key words: Electric vehicle, hill starting, luenberger observer, control strategy

INTRODUCTION

Now-a-days, the Electric Vehicle (EV) is an important way to solve the problem of environmental pollution because of its low noise, non-pollution, diversification of energy sources and high energy efficiency (Jeong and Lee, 2011; Moriya *et al*., 2002). With the rapid increasing of vehicle number in Chinese major cities, the road congestion is becoming more and more serious, especially on the overpass. Many Internal Combustion Engine (ICE) vehicle drivers will be inclined to stall when starting on hill and even slip due to lack of experience (Haifeng *et al*., 2007). Same problem exists for electric vehicle and the EV also requires the hill starting process could adapt to the changes of the external driving conditions (Xiusheng *et al*., 2010), so, it is very important to study the hill starting process of electric vehicle.

The road slope is an important parameter to the starting control process, the correct identification of the road slope has an important significance to develop the starting control strategy. Jin *et al*. (2002) presented a road slope recognition technology based on the longitudinal dynamic. It calculated the road slope according to the acceleration changes with the gradient resistance at the same vehicle speed and throttle opening. This is a kind of numerical model method which needs plenty of experience. And it is also limited by different vehicle types. Yang *et al.* (2002) used an acceleration sensor which could identify the road slope by analyzing the signals, such as the vehicle acceleration and the axle speed. The cost of the sensor also limited its application.

In studies about starting control of electric vehicle (Delvecchio *et al*., 2009) designed a Hill Start Assistance system for commercial vehicles to make the starting process smooth. Wang *et al.* (2009), the combined simulation model of the vehicle and the motor was built in the acceleration process of EV. By using the speed and current double-closed-loop control strategy, the motor could obtain a good mechanical property and realize the starting control in the motor level. However, the driver's intention was less reflected. Other studies about hill starting mainly focused on ICE vehicle and most of them made the hill starting control strategy based on the Hill-start Assist System (HAS) system in the AMT vehicle.

Considering the starting resistance and the clutch work conditions (Haifeng *et al*., 2007) accurately judged the Hill Starting Aid (HSA) valve releasing time by adding torque sensor in the HAS system, but the extra cost brought by torque sensor limited the wide application of this system. Ge *et al.* (1998) formulated the AMT vehicle's hill starting strategy and had achieved good effects by test. Chen and Kong (2011) satisfies the requirements of starting process via controlling the clutch, so there is no reference value to the EV which hasn't clutch.

In general, the smooth starting of ICE vehicle was realized mainly by the clutch or the torque converter but the electric vehicle which studied on in this study is a fixed gear ratio EV, it means that the motor is directly connected to the drive shaft with a fixed gear ratio reducer. So, the starting control strategy is greatly different from ICE vehicle because the clutch has been

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canceled and the smooth starting of EV was realized by controlling the motor torque adapting to the vehicle driving condition. Therefore, this study will design a Luenberger observer based on the vehicle longitudinal dynamics equation to recognize the road slope online. The vehicle starting resistance would also be calculated on this basis so as to solve the function trigger and HSA valve control problem of the HAS system.

METHOD OF ROAD SLOPE RECOGNITION

Hill driving force analysis of electric vehicle: The hill driving force of electric vehicle is shown in Fig. 1.

These forces include the vehicle driving force F_t, the rolling resistance F_f, the air resistance F_w and the slope resistance F_i. The acceleration resistance could be ignored during hill driving, so according to the vehicle dynamics and the Newton's second law, the equation of hill driving can be obtained, as:

$$m\dot{v} = F_t - F_f - F_i - F_w = \frac{Ti\eta}{r} - mgf\cos\gamma - mg\sin\gamma - \frac{C_D A v^2}{21.15} \quad (1)$$

where, T_t is the vehicle driving torque; T is the motor output torque; i is the speed ratio of driveline; η is the efficiency of driveline; G is the gravity of vehicle; f is the rolling resistance coefficient; γ is the road slope; C_D is the coefficient of air resistance; A is the windward area of vehicle; v is the vehicle speed; m is the quality of vehicle; r is the rolling radius of driving wheel.

Equation of system state space: The following liner processing on Eq. 1 is to reduce the complexity of the model:

- The maximum climbable gradient of electric vehicle is less than 25% in this study, so sin γ≈γ, cos γ≈1; 2. Set up $F_S = F_t\text{-}F_f\text{-}F_w$, so, the Eq. 1 could change into:

$$mv = F_S\text{-}mg\gamma \quad (2)$$

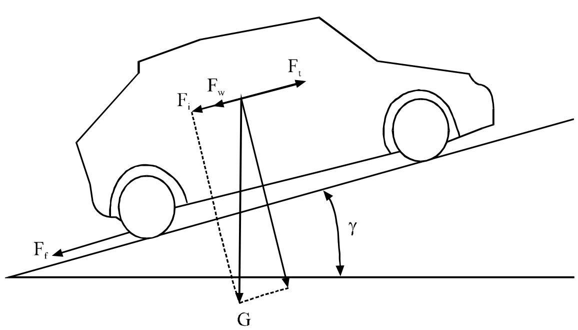

Fig. 1: Force analyze when the vehicle driving on hill

And the following is a discretization result of Eq. 2:

$$\begin{cases} \dot{x} = Ax + Bu \\ y = Cx \end{cases} \quad (3)$$

Where:

$$A = \begin{bmatrix} 0 & 0 \\ 0 & -g \end{bmatrix}, B = \begin{bmatrix} 1/m \\ 0 \end{bmatrix}, C = \begin{bmatrix} 1 & 0 \end{bmatrix}, x = \begin{bmatrix} v \\ \gamma \end{bmatrix}, \dot{x} = \begin{bmatrix} \dot{v} \\ \dot{\gamma} \end{bmatrix}, y = v, u = F_S$$

Because the Luenberger observer requirements the system has the observability, so it means the matrix:

$$Q_0 = \begin{bmatrix} C \\ CA \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & -g \end{bmatrix}$$

must be a full rank matrix. According to calculation, the rank of Q_0 is 2, so, the system is observable. Pole assignment method can be used to design the observer (Liu, 2006).

Design of the Luenberger observer: The state equation of Luenberger observer is shown as follow (Liu, 2006):

$$\begin{cases} \dot{x}_L = Ax + Bu - HC(Y_L - Y) \\ \dot{y}_L = C\dot{x}_L \end{cases} \quad (4)$$

where, x_L is the state of model; y_L is the output of model; H is the feedback gain matrix of state observer; according to Eq. 3 and 4, the error vector can be shown as:

$$\dot{x}_L - \dot{x} = (A - HC')x_L - (A - HC')x = (A - HC')(x_L - x) \quad (5)$$

When $xL(t_0) = x(t_0)$, the equation $x_L(t) = x(t)$ is correct, so the feedback of output doesn't work, it only works in the situation of $x_L(t_0) \neq x(t_0)$. As long as the eigenvalue of the matrix A-HC has a negative real part, the error of initial state vector will always attenuate by index law and the rate of attenuate depends on the pole assignment of the matrix a-HC to ensure the observables converged to the actual value (Liu, 2006; Li and Li, 2006). The structure of the designed Luenberger observer is shown in Fig. 2.

Where, F_S and v are input signals, v is the signal of vehicle speed sensor and the road slope γ can be estimated online.

The order of the system is 2 and it is necessary to configure the system's poles appropriately. The characteristic polynomial of the Luenberger observer is shown as follow:

$$f(\lambda) = |\lambda I - (A - HC)| = \left| \begin{bmatrix} \lambda & 0 \\ 0 & \lambda \end{bmatrix} - \begin{bmatrix} 0 & -g \\ 0 & 0 \end{bmatrix} + \begin{bmatrix} h_1 & 0 \\ h_2 & 0 \end{bmatrix} \right| = \lambda^2 + \lambda h_1 - gh_2 \quad (6)$$

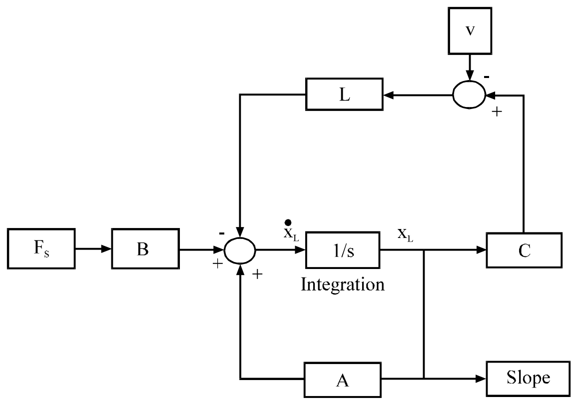

Fig. 2: Structure of the designed luenberger observer

Set a and b as the eigenvalue of the matrix H, so the Eq. 6 changes into:

$$f(\lambda) = (\lambda\text{-}a)(\lambda\text{-}b) = \lambda^2\text{-}(a+b)\lambda+ab \quad (7)$$

The two elements of the H matrix are shown as follow:

$$h_1 = -(a+b) \quad h_2 = -ab$$

The method of choosing the eigenvalue of H matrix is included (Barrho *et al*., 2005):

- The value must be negative; otherwise the system will be unstable
- If the distance between the eigenvalues and imaginary axis is too far, the sensitivity of noise will increase
- If the distance between the eigenvalues and imaginary axis is too near, the response of system will be slow

According to these restrictions, set a = b, b = 3, so:

$$H = \begin{bmatrix} 5 & 0 \\ -6/g & 0 \end{bmatrix}$$

Slope recognition precision analysis: In order to explain the precision of Luenberger observer, this study built a MATLAB/simulink model shown in Fig. 3. According to the vehicle's driving conditions, the inputs of the model include the road slope (positive means uphill, negative means downhill), the vehicle's weight m and vehicle speed and then F_S could be calculated. Finally, comparing the observed and real road slope could analyze the Luenberger observer's precision.

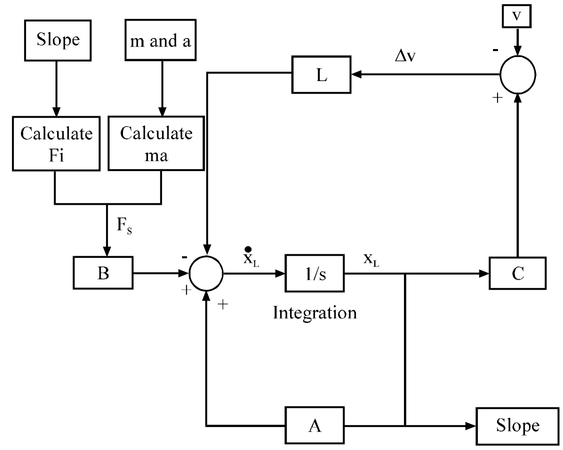

Fig. 3: Simulation model of road slope recognition precision

Table 1: Recognition results of the luenberger observer

Slope (%)	Speed	Identify slope (%)	Error (%)
0	Uniform	0.0	0
10	Uniform	9.9	1
10	Deceleration	9.9	1
20	Uniform	19.8	1
20	Deceleration	19.8	1
-10	Acceleration	-9.9	1
-20	Acceleration	-19.8	1

Table 1 shows the results of the Luenberger observer's precision. The results show that no matter the vehicle is on uphill or downhill, the observer always has a high precision and the error is less than 1%.

STARTING CONTROL OF ELECTRIC VEHICLE BASED ON HAS

Structure and function of hill assist system (HAS) in electric vehicle: The function of HAS is that even if the driver does not depress the brake pedal, the vehicle can also keep braking force temporarily and doesn't slip by the control of ECU in state of hill starting or hill parking. When the vehicle needs to start, it can release the braking force automatically to complete the starting process successfully (Ge *et al*., 1998). The basic structure and principle of the HAS are as follow: The vehicle can maintain or release the braking force though ECU to control the ON/OFF which is in the electromagnetic coil of solenoid valve, by installing solenoid valve and check valve in the hydraulic circuit between the brake master cylinder and wheel cylinder like Fig. 4. In general, the electromagnetic coil is in the OFF state with no excitation, the HSA valve is opened, the brake works normally. When the braking pressure needs to be kept during hill starting, the electromagnetic coil is in the ON state, the HSA valve is closed to cut off hydraulic loop between the brake wheel cylinder and the brake cylinder, so the oil pressure in the wheel cylinder could be kept. If the driver feels the braking force is not enough, he can depress the brake pedal to increase the oil pressure through the check valve which is parallel with the HSA valve and then, the braking force could be increased. During the hill starting process, the electromagnetic coil will be in OFF state when the driving force is higher than the starting resistance, so the oil cycle will be opened and the oil pressure released. Then the braking state will be ended and it can avoid the vehicle slipping and make the hill starting process smooth.

Hill starting integrated control of electric vehicle: The integrated control of hill starting aims at achieving a safe and smooth starting process according to the driver's intention. It contains motor control, resistance calculation and the control of HSA valve. Figure 5 shows the schematic diagram of this integrated control. Wherein, the motor control is mostly based on the drive torque corresponding with the position of accelerator pedal. This study focuses on discussing the calculation of the resistance during vehicle start on hill and the control of HAS, it includes HAS function trigger and HSA valve control logic.

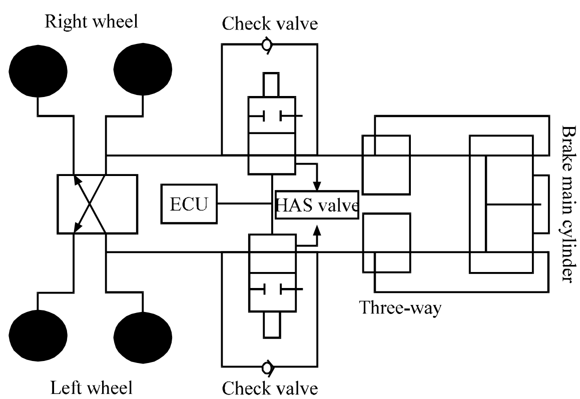

Fig. 4: Electro-hydraulic structure of HAS

Starting resistance is an important parameter to starting control. Data show that when the electric vehicle starts on hill, the road conditions are substantially as same as the time before the driver depressed the brake pedal to stop the vehicle (Ge *et al*., 1998). The air resistance is proportional to the square of the vehicle speed, so it can be ignored for the low vehicle speed during hill starting and the acceleration resistance also could be ignored similarly. So, resisting torque T_γ during hill starting primarily contains slope resistance T_i and rolling resistance T_f:

$$T_\gamma = T_i + T_f = mgfr\cos\gamma + mgr\sin\gamma \quad (8)$$

where, m can be detected by vehicle weight sensor, g is a constant, r is the vehicle structural parameter, γ has been identified by the observer and the rolling resistance torque is related to the rolling resistance coefficient. Road rolling resistance coefficient is generally determined by experiments, it's hard to identify this parameter of each road. In order to avoid vehicle slipping caused by HSA valve prematurely releasing on bad road, this study

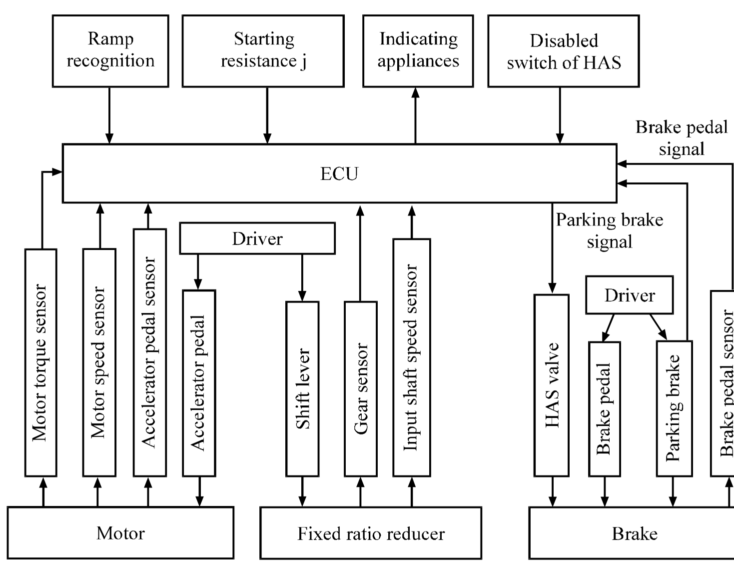

Fig. 5: Schematic diagram of hill starting integrated control

properly amplifies the rolling resistance coefficient by replacing it with the counterpart of potholes pebble road and the value is about 0.04.

The mentioned function trigger of the HAS in this study belongs to an active control strategy. It can be triggered automatically. Through the real-time tracking of the road state recognition as mentioned in previous segment, each new result has to replace the previous result to ensure the road slope saved in ECU accurately. This process will last until the time when the brake pedal begins to work and the value will be used to trigger the HAS function during the vehicle's next starting (Xiao, 2009; Yan, 2009). The results of experiments show that when a vehicle on a hill which has a ramp angle less than 2° with no braking force, it will not slide even the shift lever is in neutral state. So, the HAS function can only be trigger when the vehicle is on a hill which has a ramp angle more than 2° (Haifeng *et al*., 2007).

The key issue of HAS control is the ON/OFF control of HSA valve, including the start moment and release moment of the valve. The ECU collects the vehicle running state data via sensors and some kinds of algorithms to decide ON/OFF the HSA valve. Control signals input to ECU includes the following sections: (1) Motor start signal, (2) Motor output torque, (3) Accelerator pedal signal, (4) Input axis rotational speed signal, (5) Gear shifting signal, (6) Brake pedal signal, (7) Parking brake signal (8) HAS disable switch signal (9) Recognition result of starting resistance torque (10) Vechile weight signal.

If all the following conditions are satisfied, the HSA valve will be electrified and shut down and the braking force will be maintained (Ge *et al*., 1998; Xiao, 2009; Yan, 2009):

(1) Parking, (2) Motor starting, (3) Vehicle is in gear, (4) Braking pedal is depressed, (5) The HAS function be triggered, (6) HAS disable switch is on OFF state.

The parking state is judged by whether the input axis has a zero rotational speed (the number of pulses is zero in 0.2 sec). Condition 1 is mandatory brake when the driver didn't make any mistakes, conditions 2 and 3 are measures to avoid the HAS working when parking braking, conditions 4, 5, 6 are the keys to run HAS control.

If any of the following conditions is satisfied, the HSA valve will be power off and the braking force will be relieved (Ge *et al*., 1998; Xiao, 2009; Yan, 2009):

- Accelerator pedal is depressed and motor output torque greater than calculated starting resistance torque
- Exist forward direction speed signal on input axis
- Exist parking brake signal
- HAS disable switch is in the ON state

Condition 1 and 2 are the keys to relieve braking force and they are the key points for a vehicle to start smoothly. In addition, parking brake will be done when the driver hope to park the vehicle for a long time, in this situation, the HSA valve should be power off. Condition 4 actually is a manual operation from the drivers and it should be satisfied.

The above control logic show that the HAS adapts to vehicle hill starting but can not work in parking situation for a long time, however, it can make the system more stable.

SLOPE RECOGNITION AND HILL STARTING SIMULATION

Figure 6 shows the simulation results of the slope recognition, this study assumes that the vehicle speed is a constant and then simulation with different F_S. As the

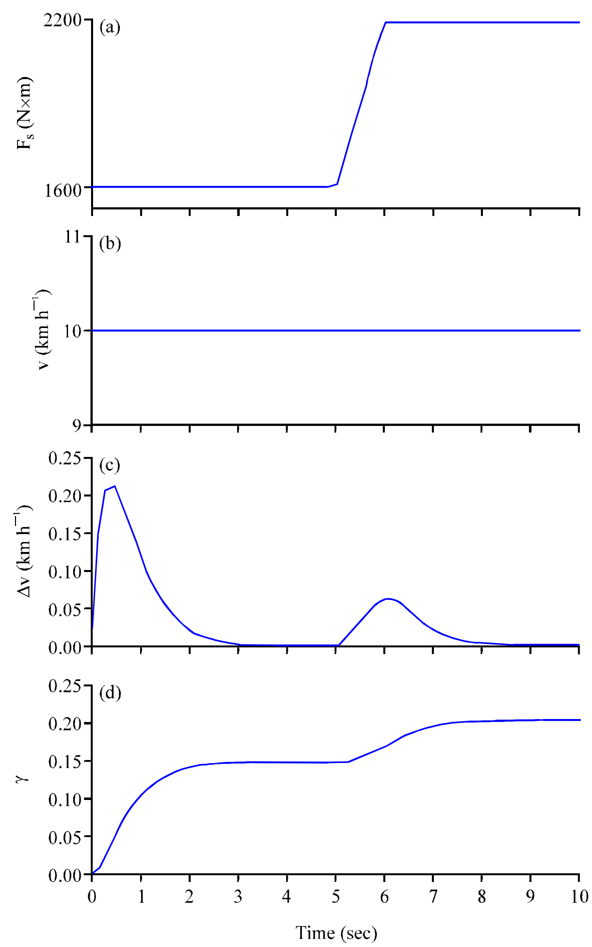

Fig. 6(a-d): Simulation results of slope recognition, (a) Curver of FS changes with time, (b) Vehicle speed (c) Input signal of observer feedback gain matrix changes with time and (d) Results of ramp recognition

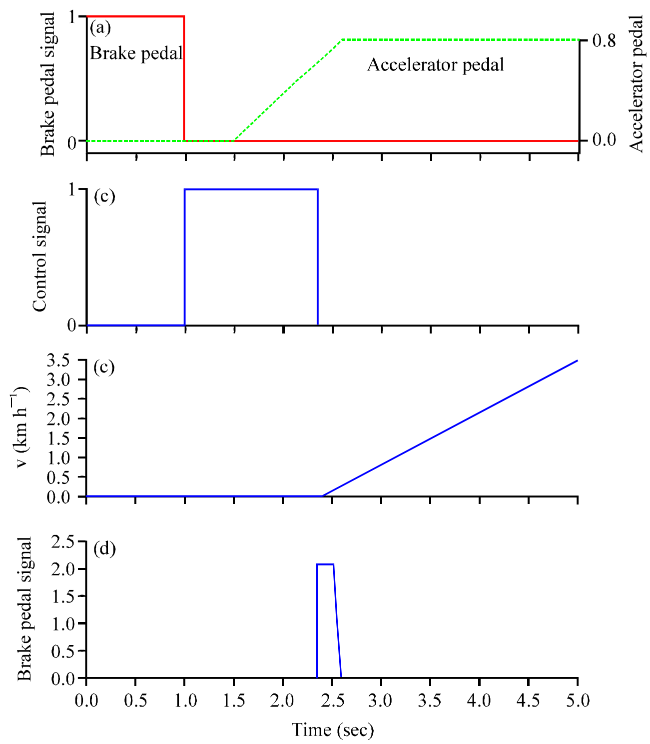

Fig. 7(a-d): Starting simulation results on a 15% slope hill with full load, (a) Pedal opening changes with time, (b) Control signal of HAS valve, (c) Vehicle speed simulation results and (d) Jerk simulation results

Table 2: Key technical parameters of electric vehicle

Parameters	Value
Non-load mass (kg)	950.0000
Full load mass (kg)	1100.0000
Wheel radius (m)	0.2620
Reducer ratio	5.2200
Rolling resistance coefficient	0.0400
Motor peak torque (N×m)	150.0000
Correction coefficient of rotating mass	1.0500
Average transmission efficiency	0.9000

system itself has the response time, so in the results, the observer feedback matrix input signal Δv was larger in the first 2 sec and the road slope obtained was 14.8% after 2 sec and then because the system input F_S increased after 5 sec, the road slope increased to 20.4% accordingly. From this result, the precision of the designed Luenberger observer is verified.

In the hill starting simulation, this study takes an electric vehicle which is modified from an A0 level vehicle as the research object and Table 2 shows the key technical parameters of electric vehicle.

Figure 7 shows the simulation results of the hill starting on a 15% ramp with full load. The curve indicates that the system trigger the HAS function automatically via the slope recognition. When the driver depressed the brake pedal, the HSA valve power off and the brake pressure will be held. After 1 sec, the brake pedal was released but the HSA valve also on off state. After 1.5 sec, the driver depressed the accelerator pedal and the motor driving torque was greater than the starting resistance at 2.3 sec, then the HSA valve power on, the braking force was released, then the vehicle start smoothly. Figure 7d indicates that the jerk during the starting process was less than 2.5 m sec^{-3}, the ride comfort is very good. During the whole process, the vehicle didn't slip, the control effect is satisfactory.

CONCLUSION

- The longitudinal dynamics equation of the electric vehicle hill starting had been analyzed; the state equation had been achieved by linear process and the system's observability had been determined based on the equation; a Luenberger observer had been designed by configured the pole of the system reasonably to recognize the road slope online

- Hill starting integrated control of electric vehicle based on the HAS had been proposed; the starting function trigger in HAS, calculation of starting resistance and the control logic of HSA valve had been solved; the simulation results showed that the proposed method could satisfy the requirement of electric vehicle hill starting and there was no slip during the starting process and the jerk was less than 2.5 m sec^{-3}, the starting ride comfort is good

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