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Simulation analysis of electric window anti-pinch based on speed difference method

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Abstract: With the continuous development of the automobile industry and people's increasing emphasis on automobile safety, anti-trapping of electric windows as an important safety function has attracted more and more attention from users. This paper studies the speed difference-ripple scheme of electric window anti-pinch, analyzes the theory of speed difference method, and expounds the principle and application of ripple technology. Simulink software is used to model and simulate the current and speed difference, which verifies the feasibility and effectiveness of the scheme. The research results show that the speed differential method-ripple scheme is a feasible and effective anti-pinch technology for electric windows, and it has broad application prospects compared with the traditional Hall sensor anti-pinch technology.

1. Introduction

With the rapid development of modern automotive electronic technology, more and more new technologies are being applied to cars. One of them is the automation of car windows, where automatic up and down windows have gradually replaced traditional manual windows as the mainstream. Due to the improvement in the level of automation and intelligence of car windows, the glass of the car window can produce excessive tightening force during the automatic up and down process, which poses a safety hazard to human beings and has become a significant issue that cannot be ignored [7]. Therefore, research on electric window anti-pinch technology has become increasingly necessary.

To solve the safety hazard of electric windows, many countries have enacted relevant laws and regulations, requiring car manufacturers to apply safety measures in the design of car windows. For example, the European Union has enacted standard 74/60 EEC, the United States has enacted standard FMVSS118, and China also released national standard GB11552-2009 in 2009, which specifies the specifications for electric car windows [1] and clarifies the design and manufacturing standards for electric car windows.

Currently, the main technology used for window protection is based on a Hall sensor. The anti-pinch technology based on Hall sensor has a considerable development history, high maturity level, and a wide range of applications. In contrast, the anti-pinch technology based on ripple motors has a shorter development time, relatively little research, and its technological development is not mature enough. However, due to its low cost, the anti-pinch technology based on ripple motors still has significant research value and significance.

2. The Composition and Anti-Pinch Principle of Car Windows

2.1. Composition of Car Windows

The power window system consists of a DC motor, a worm gear, a pulley, a flexible connector, a steel cable, a window guide rail, a pulley, and related rubber components. Among them, the pulley can convert curved motion into linear motion [5]. The structure of the power window glass lifting system is shown in Figure 1.

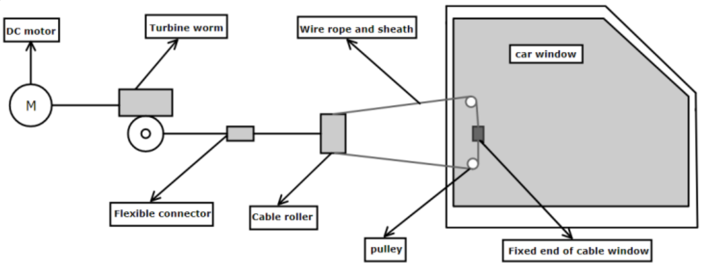

Figure 1: Schematic diagram of car window system structure.

2.2. Anti-pinch Standard

2.2.1. Anti-Pinch Area

The anti-pinch area of the car window is shown in Figure 2, which includes the area within 4mm to 200mm from the top of the power window. This definition meets the relevant requirements of the European 74/60/EEC standard and the American FM-VSS118 standard [2].

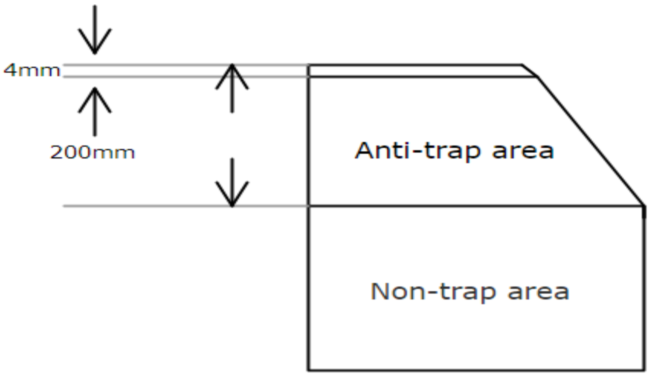

Figure 2: Schematic diagram of anti-pinch area.

2.2.2. Anti-pinch Force

The anti-pinch force refers to the maximum force that can be applied to the object being pinched during the anti-pinch process of the electric car window. This definition is determined according to the GB 11552-2009 standard. When the automatic window reverse function is used, the anti-pinch force should be less than or equal to 100N.

Therefore, the conditions that must be met when the car window is equipped with anti-pinch measures are: (1) the window is in the up position, (2) the window is in the anti-pinch area, and (3) the pinch force on the window is greater than 100N. When all three conditions are met, the anti-pinch system of the car window adopts anti-pinch measures to lower the window glass.

2.3. Principle of Anti-pinch

2.3.1. Criteria for judging anti-pinch based on ripple

Principle of ripple generation: When the DC motor changes direction, different paths are formed, resulting in a change in circuit voltage. This causes the current to pulsate periodically, forming current ripple. The number of motor rotations from the lower end to the upper end of the car window is fixed, and the number of pulsations produced by one motor rotation depends on the number of commutator segments and the number of poles. The number of commutator segments and poles of each motor is fixed. Therefore, the number of ripples produced by one motor rotation is also fixed. The frequency of the current ripple is f=kn, where k is the number of commutator segments and n is the motor speed. Therefore, the position of the car window glass can be determined by detecting the current ripple of the lifting motor [4].

2.3.2. Criteria for judging anti-pinch based on speed difference

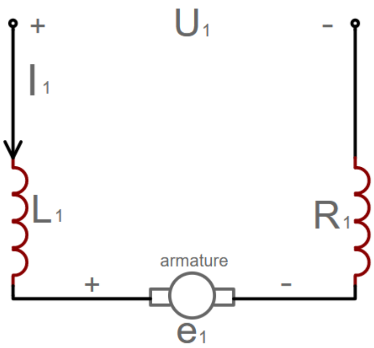

Figure 3: Equivalent circuit diagram of DC motor.

As shown in Figure 3, it is the equivalent circuit diagram of a DC motor. The inductance, resistance and armature constitute the DC motor, where the resistance is the steady-state part, and the inductance and armature are the transient parts. Based on the voltage relationship and torque balance of the equivalent circuit, formulas (1) and (2) can be obtained.

$$\frac{di_1}{dt} = \frac{U_1 - R_1 - K_e\omega_n}{L_1} \tag{1}$$

$$\frac{d\omega_n}{dt} = \frac{K_T - T_L - B\omega_n}{J} \tag{2}$$

In the formula, i_1 is the circuit current; U_1 is the circuit supply voltage; R_1 is the equivalent internal resistance; ω_n is the DC motor speed; L_1 is the equivalent inductance; K_e is the magnetic circuit linear induction constant; K_T is the magnetic circuit mechanical linear induction constant; T_L is the load torque; B is the magnetic field strength; J is the moment of inertia.

To investigate the relationship between torque and speed, only the steady-state operation of the motor is considered, assuming that the current (i_a) and angular speed (ω_n) have reached steady state. The expression (3) for the relationship between the speed and the load torque of the DC permanent magnet drive motor can be obtained. The magnetic circuit linear induction constant, magnetic circuit mechanical linear induction constant, magnetic field strength, and internal resistance are all constants in equation (3), so the equation (4) for the relationship between motor speed and load torque can be obtained.

$$\omega_n = \frac{K_T U_a}{BR_1 + K_e K_T} - \frac{R_a T_L}{BR_1 + K_e K_T} \tag{3}$$

$$n = K_1 U_a - K_2 T_1 \tag{4}$$

In the equation, n represents the motor speed; K_1 is the voltage influence factor, $K_1=K_T/2\pi(BR_a+K_eK_T)$; K_2 is the torque influence factor, $K_2=R_a/2\pi(BR_a+K_eK_T)$.The expression for the relationship between the motor speed and torque at the turbine location is:

$$n_w = K_{1'} U_a - K_{2'} T_w \tag{5}$$

In the equation, n_W is the speed of the turbine, T_W is the torque of the turbine, i is the transmission ratio of the turbine worm, $K_{1'}$ is the voltage influence coefficient, $K_{1'} = K_1 \times i$, and K_2 is the torque influence coefficient, $K_{2'} = K_2 \times i_2$. Through the force analysis of the entire mechanical system of the car window, the relationship between the turbine torque and the driving force of the motor can be obtained:

$$T_w = F_A \times R \tag{6}$$

In the equations, F_A represents the driving force of the motor, and R represents the radius of the winding wheel.

Under normal operating conditions of the car window, the speed, voltage, torque, and ripple period are represented by n_R, U_R, T_R, and t_R, respectively. When the anti-pinch force F_O is set to 80N, the speed, voltage, torque, and ripple period are represented by n_0, U_0, T_0, and t_0, respectively. By substituting these parameters into equations (5) and (6), we obtain the formulas:

$$n_R - n_o = K_{1'}(U_R - U_o) + K_{2'} F_o R \tag{7}$$

Each revolution of the motor produces 8 current ripples, which leads to a relationship between the turbine speed and the motor ripple period.

$$n_w = \frac{60i}{P_t} \tag{8}$$

The expression for the anti-pinch judgment can be obtained from equations (7) and (8):

$$\frac{60_i}{P_t R} - \frac{60i}{P_t o} \rangle K_{1'}(U_R - U_o) + K_{2'} F_o R \tag{9}$$

From reference [3], we know that $K_{1'}=6.179$ and $K_2'=5.682$. The threshold value of speed difference is set to 10, i.e. the difference between the rated speed and the anti-pinch speed is 10 r/min. From the above equations, we can obtain the relationship between the motor current i and the turbine output speed n_w is:

$$n_w = 60i/(P_t \times R) - 10 \tag{10}$$

Here, Pt represents the number of current ripples generated by the motor per revolution, R is the radius of the turbine, and 10 is the selected value for the speed difference.

3. Modeling and Simulation of Car Window Anti-Pinch System

3.1. Simulation Parameter Calculation

Before constructing the Simulink simulation model, it is necessary to calculate the relevant parameters. First, the period of the current ripple needs to be calculated. The frequency of the current ripple is f = kn, and the commutator number k is 1. The motor speed can be calculated as n, and the period of the current ripple is t. Another parameter to consider is the load torque of the car window lifting motor. The weight of the car window glass and the 80 N resistance are converted into the load torque of the turbine and the winding wheel. The derivation process of the load torque on the turbine and winding wheel due to the weight of the car window glass is shown in [6]:

$$F = \frac{\mathrm{mg}}{\eta_1} \tag{11}$$

$$T' = \frac{F\frac{D}{2}}{\eta_2} \tag{12}$$

$$T'' = T_L = \frac{T'}{K\eta_3} \tag{13}$$

The specific parameters were calculated and are shown in Table 1:

Table 1: Simulation Parameters

Parameter	Value
Current ripple frequency f	108 Hz
Current ripple period t	0.00926 s
Motor speed ω	6497 rpm
Window glass weight m	3.3 kg
Wire rope tension F	41.25 N
Sliding rail efficiency η_1	80%
Torque on turbine and pulley T'	1.31484375 N.m
Pulley diameter D	0.051 m
Wire rope pulley efficiency η_2	80%
Efficiency of turbine worm gear transmission η_3	40%
Transmission ratio K	89
Load torque on motor shaft (when encountering 80 N resistance)	90 mN.m
Output torque of motor T''	37 mN.m

3.2. Analysis of Anti-Pinch Control Process for Car Windows

The entire control process of the electric car window should meet the following requirements:

(1) The window must be fully opened or closed within 5 seconds during normal lifting and lowering.

(2) The window must start moving within 0.2 seconds after the button is pressed.

(3) When the window reaches the fully open or fully closed position, it must stop.

(4) The window must be able to detect an additional load torque of 112 mN.m as an obstacle. If an obstacle is detected, the window must be lowered by about 10 cm.

(5) The driver's side window control has higher priority than the passenger's side.

The anti-pinch control process of the electric car window based on the speed difference method is shown in the Figure 4:

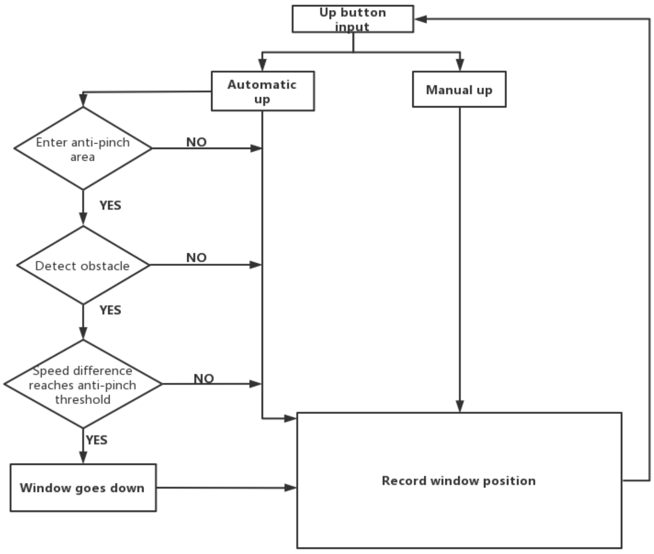

Figure 4: Control flowchart

3.3. Establishment of Simulation Model and Analysis of Results

In this paper, a current ripple-based anti-pinch system for car windows was modeled and simulated using Simulink software, and a simulation model of an electric car window system was constructed. The model is based on Simulink's DC Machine DC motor model and uses the load input module shown in Figure 5 to simulate the load conditions of the electric car window system. Signal 1 represents the torque of the window when it is blocked in the anti-pinch area, signal 2 represents the load torque of the window glass, signal 3 represents the torque when the window is raised, and signal 4 represents the blocked torque when the window has not reached the anti-pinch area. Meanwhile, the signal input module shown in Figure 6 is used to simulate the lifting and lowering signals of the car window. During the simulation of the normal lifting and lowering process of the car window, simulated load inputs were added to simulate situations where the window is blocked during normal upward movement. Finally, the simulation results were evaluated and analyzed by observing the motor current, angular velocity, and speed images output by the oscilloscope, in order to better understand and optimize the operation of the electric car window system.

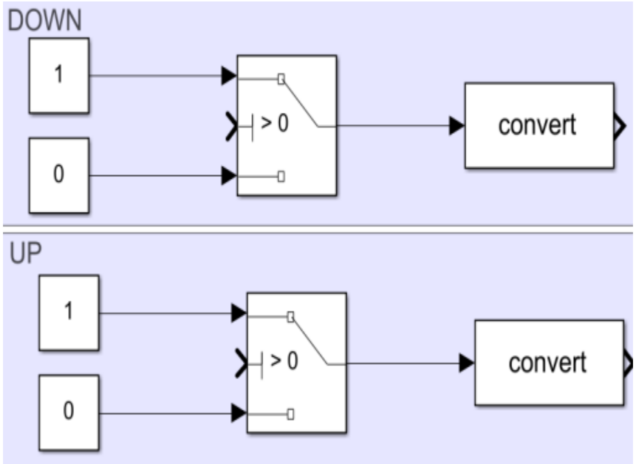

Figure 5: Signal Input Module

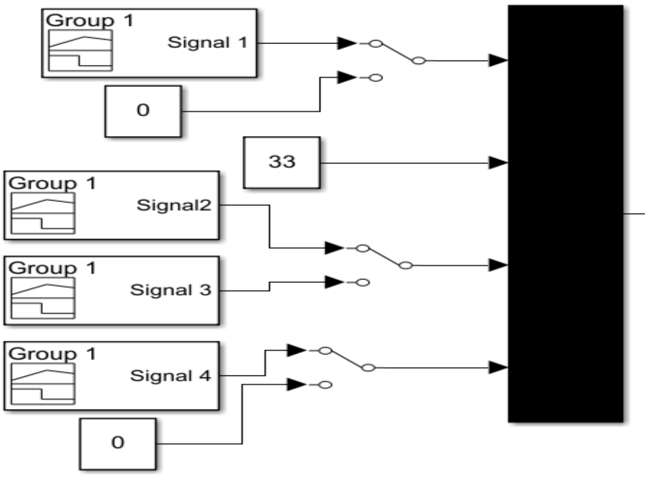

Figure 6: Load Input Module

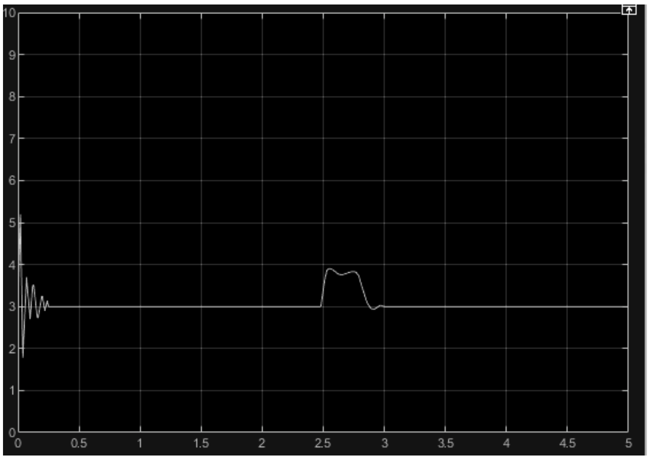

Figure 7: Simulation waveform of motor current

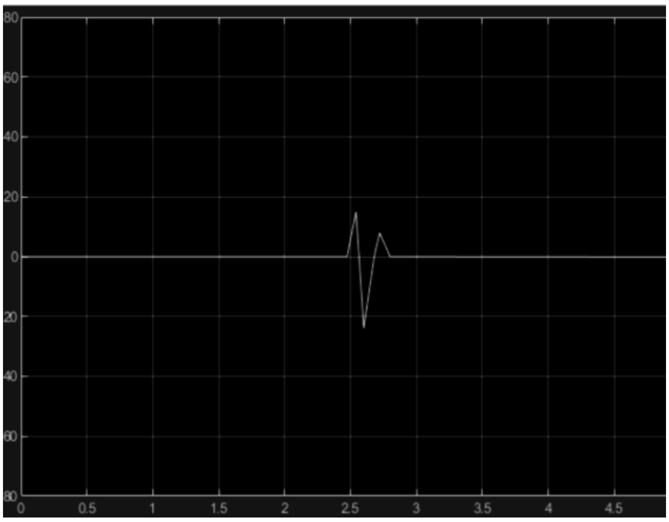

Figure 8: Simulation waveform of speed difference

The results obtained from the simulation model built based on Simulink software are shown in Figures 7 and 8. When the input load encountered resistance in the anti-pinch area, a pinch event occurred in the car window, leading to the motor current exceeding 3.5 A. Additionally, due to the occurrence of the pinch event, the motor speed also decreased at the same time, and the difference between the anti-pinch speed and the rated speed increased to 17. Finally, at around 2.6 seconds, the car window successfully took anti-pinch measures and achieved safe operation.

4. Conclusions

In summary, this paper utilized Simulink software to construct a simulation model of an electric window system, and simulated the window's up and down movements and anti-pinch situations using signal input and load input modules. By evaluating and analyzing the simulation results, it was demonstrated that using the speed difference method can achieve quick and accurate anti-pinch measures, effectively avoiding potential harm to personal safety and property caused by pinching events, and providing important references for optimizing the design and operation of electric window systems. In conclusion, this study provides a feasible solution for the anti-pinch control of electric window systems.

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