Research on Anti-pinch Control Strategy of Window Start-up Phase based on Ripple Motor

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Abstract. The anti pinch area of power windows is generally 4 mm-200 mm based on ripple motor. However, the problem of excessive anti-pinch force is most likely to occur when starting at 4mm during the process of window operation. Aiming at this problem, this strategy takes current, current change rate and start-up time that can characterize the start-up phase of the window as input according to the characteristics of fuzzy control that has better recognition for unstable starting current. Then, according to the actual engineering experience is used as a fuzzy rule to make a decision on the current start-up state of the window. Finally, the state is used as the input for the anti-pinch control strategy. The compensation mechanism based on the Freeplay is added to the strategy. The current state is used to design the current threshold to realize the control of the anti-pinch force during the start-up phase. The results show that the strategy can effectively reduce the anti-pinch force in the start-up phase, it can make the anti-pinch force less than 100N and meet the requirements of GB11552-2009.

1. Introduction
The operation of the electric window is driven by the motor, and there is a risk of injury during the closing of the window [1]. At present, the anti-pinch technology of car Windows is mainly composed of Hall anti-pinch technology [2] and ripple anti-pinch technology [3]. Hall anti-pinch technology is to install a magnetic ring on the rotating shaft. According to the Hall effect, when the motor rotor turns once, a square wave pulse signal is generated by the Hall sensor, and the number of pulse signals is captured by the internal clock module, so as to determine the position of the power window [4]. Ripple anti-pinch technology is mainly based on the fact that the current will fluctuate due to the change of resistance when the brush is in contact with the two commutator segments. Each time the brush is commutated, there will be a fluctuation. If the motor has N pairs of windings, the frequency of the ripple generated by the armature rotation is 2N. By counting the number of fluctuations, the speed information and position information of power window can be calculated.

Jung Hoon Park Won et al. [5] proposed kalman filter anti-pinch scheme and anti-pinch algorithm based on state estimator. By designing state estimator, the influence of interference information on the system can be suppressed and filtered. However, these schemes lack the analysis of input interference signals. The state of the window is very unstable during the start-up phase, it will tend to lead to deviation and divergence of the estimated value, the response time of the window reversal will increase, and anti-pinch force will rise rapidly.

In the current detection scheme proposed by scholars represented by Angelo [6], it adopts the detection method to determine whether the motor current exceeds the set threshold value to prevent anti-pinch event. Due to the disturbance factors such as changes in the external environment, motor load will...
change and the current signal contains a lot of interference information, it will leading to the instantaneous peak of current exceeding the anti-pinch threshold and thus the false reversal of the window.

Scholars such as Liu Guangmin [7] from the Institute of Automation of Shandong Academy of Sciences adopted sensorless electric window anti-pinch control module to realize anti-pinch of power window. By sampling the current passed by the window lifter motor, it can monitor the change of resistance during the window process to perform the corresponding operation. However, in the start-up phase of the window, the instantaneous current change of the motor may have a peak value, it leads to the occurrence of the false reversal event.

According to the current situation, the current anti-pinch control strategies rarely consider the problem of excessive anti-pinch force and wrong anti-pinch caused by the characteristics of ripple motor start-up phase. In this paper, freeplay detection mechanism of window motor is introduced to solve the problem of unstable current in the start-up phase of ripple motor. This paper mainly aims at the matching of control parameters and subjective experience in the start-up phase of ripple motor, which can effectivly optimize the anti-pinch control strategy in the start-up phase of window and reduce the anti-pinch force in the start-up phase.

2. Requirements and analysis of window start-up phase

2.1 Current state analysis at start-up phase

When the motor reverses, there is a gap between the gears in the start-up phase of the motor. This state is called the Freeplay state. As the anti-pinch force is positively correlated with the current, the ripple current after low-pass filtering with or without Freeplay waveform at the start-up phase as shown in Figure 1(a) and Figure 1(b).

![Figure 1. Start-up phase current](image)

(a) Start-up phase current with Freeplay  
(b) Start-up phase current without Freeplay

As shown in Figure 1(a), the start-up phase of the motor is divided into 5 states. In the state 1, the motor is in the start-up phase and the time is 0-10ms. In this state, the motor idles and the speed is 0, so there is no counter electromotive force(emf) at this state and current will rise rapidly within 0-10ms. The time of the state 2 is 10ms-30ms. In this state, the rotor starts to rotate due to the presence of Freeplay, the gear is not occlusive and the window is still at rest. After the gear bites, the motor starts to overcome the static friction force to drag the load, so the current will start to drop, and the rope will gradually enter the stretching state within 20ms, at last current will drop to about 2A. The time of state 3 is 30ms-60ms, the sliding friction is overcome to drag the load, and the window starts to do variable accelerated motion. The time of state 4 is about 60ms-90ms, During this period, the rising speed of the windows gradually stabilized. About 50ms later, it enters the state 5, the window has been moving at a constant speed and the current is stable. The current waveform at the start-up phase without Freeplay is shown in Figure 1(b). During the period of 10ms-30ms, the motor gear has been locked. The relation between the speed and current can be obtained from formula 1, so the motor will not cause the phenomenon of rapid current.
drop due to the sudden increase in load.

\[
\omega = \frac{U-I_a R_a}{K_{\omega} \Phi}
\]  

(1)

It can be seen from Figure 1 and 1B that the current waveform with or without Freeplay is significantly different during state 1 to 3. In the case of Freeplay, a single threshold control can easily lead to false reversal and excessive anti-pinch force. Therefore, a reasonable control strategy needs to be made in the start-up phase.

2.2 Window system control requirements

This paper is based on the ripple motor of a car door and its input and output is shown in Figure 3. T is the starting time, \(U_a\) is the motor voltage and \(I_a\) is the ripple current. In the aspect of ripple detection in this paper, \(I_{a1}\) is obtained through low-pass filtering and the speed information is obtained by counting the frequency of \(I_{a1}\), the position information is obtained by counting the number of current peaks that meet the counting threshold of \(I_{a1}\). \(I_{a2}\) is the dc component of the ripple current, the current rate of change \(\Delta I_{a2}\) and start-up time \(T\) as input, determining the current state through fuzzy control, then according to the different current state make different threshold control, final output reverse information.

2.3 Mathematical model of ripple motor

Ripple motor is a typical DC motor. The DC motor model is shown in Figure 2.

\[
U = K_{\omega} \cdot \Phi \cdot \omega + R_a \cdot I_a + L \cdot \frac{di}{dt}
\]  

(2)

\[
I_a = \frac{U - K_{\omega} \Phi \omega}{R_a}
\]  

(3)

Under ideal conditions, the current is a constant value, then \(L \cdot \frac{di}{dt} = 0\), \(K_{\omega}\) is the back electromotive force constant, \(\Phi\) is the magnetic flux, and \(\omega\) is the motor speed. \(T_m\) is the electromagnetic torque produced by the motor, which is proportional to the motor current \(i\), \(K_T\) is the motor torque constant, \(J\) is the moment of inertia, and \(T_L\) is the load torque. \(B\) is the coefficient of viscous friction. The mechanical equation of DC motor is obtained by torque balance:

\[
K_T \cdot \Phi \cdot i = B \cdot \omega + J \cdot \frac{d\omega}{dt} + T_L
\]  

(4)

After the speed is stable, the above formula is simplified and organized as

\[
F_{act} \cdot \tau = K_T \cdot \Phi \cdot i
\]  

(5)

\(F_{act}\) is electromagnetic force, from which the relationship between \(F_{act}\) and motor voltage \(U\) and speed \(\omega\) can be obtained. Because when the motor is running stably, the electromagnetic torque is equal to the load torque without considering the influence of other factors, so the electromagnetic force is positively correlated with the force \(F_1\) of the load torque. According to the anti-pinch detection condition: \(F_1 > F_{Th}\), \(F_{Th}\) is the anti-pinch force threshold, and formula 5 shows that \(F_{act}\) and \(I\) are positively correlated, so when the actual current is greater than the set current threshold, the window performs an anti-pinch reverse action.

3. Simulation and analysis of start-up current state decision control strategy

3.1 Design of start-up current state decision control strategy

According to the control strategy of window start-up phase, the current is divided into 5 states which correspond to 5 different physical states start-up phase for ripple motor, A fuzzy control algorithm which
does not depend on the precise mathematical model of the controlled object is used to make decisions on these 5 states. In figure 3, \( I_{a1} \) is armature current of dc component, \( \Delta I_{a1} \) is \( I_{a1} \) rate, \( T \) is the motor start-up time, with the three values as the input of the fuzzy algorithm. The \( \Gamma'_{a1}, \Delta \Gamma'_{a1} \) and \( T' \) are outputs after fuzzifying, \( S' \) is intermediate quantity. Through fuzzy reasoning, \( S \) is the start-up current state after the Defuzzification.

Figure 3. The function of starting current state decision control strategy in the system

The armature current can well represent the torque output, so as to supplement the integrity of the information that characterizes anti-pinch force of vehicle window. However, because the current of the ripple motor is unstable at the start-up phase and it can’t produces ripple current immediately, so it is impossible to describe current state at the start-up phase by mathematical model, but the fuzzy control algorithm can create control strategies based on the experience of engineers. Based on the above advantages, in order to improve the security and stability of power window in the start-up phase, this paper proposes an anti-pinch control strategy based on the combination of fuzzy control and Freeplay. According to the information in Figure 1a and 1b, the current state can be determined by the current in different current states, current change rate and running time. Then the anti-pinch control strategy can be designed according to the feedback control mode of detecting current.

3.2 Realization of fuzzy control compensation

This paper proposes fuzzy control to determine the current state, then uses this as a basis to control different states. In threshold compensation, current \( I \), current rate of change \( \Delta I \), and start-up time \( T \) are used to fully characterize the current state information and motor position information of the motor during the start-up phase. Through fuzzy reasoning identification, the current current is obtained. According to the identified different current states, different degrees of current threshold compensation are given to improve the safety of the vehicle's window during the start-up phase. In the specific design, firstly, it is necessary to divide the fuzzy domain and the fuzzification operation for each input and output parameters, then establish fuzzy reasoning rules, determine the reasoning method and defuzzification method, and finally defuzzify the output. Combining the information in Figure 5 and based on actual experience, the domain of \( I \) is \([0A, 16A]\), and the current size is described by three fuzzy variables, namely \( ZO \in (0, 4) \), \( PS \in (2, 8) \), \( PB \in (6,16) \). The domain of \( \Delta I \) is \([-1.5A/ms, 1.5A/ms]\), which is described by 5 fuzzy variables, \( NB \in (-1.5,-0.3) \), \( NS \in (-0.7,-0.2) \), \( ZO \in (-0.3,0.3) \), \( PS \in (0.2,0.7) \), \( PB \in (0.3,1.5) \). the domain of the \( T \) is \([0ms, 150ms]\), which is described by 3 fuzzy variables, \( ZO \in (0,50) \), \( PS \in (25,100) \), \( PB \in (75,150) \). The domain of current state is \((0, 6)\), it described by 6 fuzzy variables, respectively \( NB \in (0,1) \), \( NM \in (0,2) \), \( NS \in (1,3) \), \( PS \in (2,4) \), \( PM \in (3,5) \), \( PB \in (4,6) \). Therefore, the determination of the fuzzy rules is shown in Table 1.
Table 1. Fuzzy rules

| T     | ΔΔI | ZO | PS | PB |
|-------|-----|----|----|----|
| NB    | NM  | NM | NB |    |
| NS    | NM  | NS | NS |    |
| ZO    | NS  | NS | NM |    |
| PS    | PS  | PS | NS |    |
| PB    | PS  | PM | NS |    |
| NB    | NM  | NS | NS |    |
| NS    | NS  | NS | NS |    |
| PS    | ZO  | NS | PS | NS |
| PS    | PM  | PM | PS |    |
| PB    | PS  | PM | PS |    |
| NB    | PM  | PB | PM |    |
| NS    | PB  | PB | PM |    |
| PS    | PB  | PB | PB |    |
| PB    | PM  | PB | PB |    |

There are two types of fuzzy reasoning methods, Mamdani and Sugeno. There are maximum membership function method, simple average method and center of gravity method for defuzzification. In this paper, the Mamdani fuzzy reasoning method is used to achieve defuzzification based on the current input and it can determine the current state of the ripple motor. As shown in Figure 7, the actual current, current rate of change, and start-up time are used as inputs, and the current state of the start-up current is finally output. The structure of the fuzzy controller and the actual output current state are shown in Figure 4. After the start-up phase current passes through the fuzzy controller, the current state is output. Within 0 to 50ms, the division of the start current state 1 and 2 is realized, and the state 3, 4, and 5 are realized in 50 to 150ms. After the current has stabilized at state 5, it indicates that the current has stabilized and entered the normal phase.

4. Design of anti-pinch control strategy based on Freeplay

4.1 Anti-pinch control strategy with Freeplay during start-up phase

The traditional car window anti-pinch strategy usually adopts a single threshold. Once the motor current exceeds the anti-pinch threshold, the anti-pinch action is performed. However, due to the instability of
the current during the start-up phase, so a single threshold value needs to be avoided. The current analysis of the window motor in the starting phase is mentioned by section 2.1 and based on the fuzzy rules, the five current states of the window motor from starting to normal lifting are determined. Therefore, the recognition of these five states is extremely important for the control strategy of the start-up phase. In this design, the anti-pinch control strategy is divided into the start-up phase and the normal phase. In section 2.1, the current state of the start-up phase is analyzed. Now it is necessary to make corresponding control strategy for 5 states to prevent the occurrence of anti-pinch force greater than 100N.

In the start-up phase, due to the large current peaks of state 1 and 2, at this time, it is necessary to turn off the anti-pinch function and increase the current threshold (Normal_limit) in the normal phase to the maximum value to prevent the current exceeding the threshold. In state 3 and 4, due to the longer duration, the anti-pinch function needs to be turned on. However, due to the current change is unstable in this state, formula 4 shows that the current and the anti-pinch force are positively correlated, so the current threshold needs to be increased at this state. At last, Entering the anti-pinch strategy during the start-up phase.

In the anti-pinch control strategy in the start-up phase, according to the current state decision strategy, the actual current in the state 3 is recorded and added to the start-up phase threshold (Startup_limit) to achieve the compensation of the current in the deformation phase. In the state 4, since the current gradually stabilizes, the threshold compensation of the actual current is cancelled at this time and the constant threshold is used as the basis for reversal judgment and Startup_limit is reduced. So it achieves the purpose of reducing the anti-pinch force.

After state 5, the speed of window is constant, then anti-pinch control strategy will exit start-up phase and enters the anti-pinch control in normal phase. In normal phase, Instead, the difference (I_Ext) between the current recorded after the window is initialized and the actual current is used as judgment. If an obstacle is encountered, the actual current will be significantly greater than the current recorded during initialization. If the difference (I_Ext) at this time is greater than the normal phase threshold Normal limit, it will be recognized as a pinch object and trigger a reversal action.

(a) Anti-pinch control strategy with Freeplay
(b) Anti-pinch control strategy without Freeplay

Figure 5. Anti-pinch control strategy
4.2 Anti-pinch control strategy without Freeplay during start-up phase

For window raising without Freeplay, because the window lifter rope is always in tension, the compensation in the state 3 is much smaller than that of Freeplay, so the anti-pinch threshold at this state is generally determined by the global anti-pinch threshold. In the state 4, since the current gradually stabilizes, the threshold compensation of the actual current is reduced at this time and the constant threshold is used as the basis for the reversal judgment. However, because the compensation of No Freeplay is very small, the threshold change of the state 3 and 4 is about a constant value.

After the state 5, the window has risen at a constant speed, No Freeplay control strategy is the same as the Freeplay control strategy. It will control strategy will exit start-up phase and enters the anti-pinch control in normal phase. The control flow chart of No Freeplay is shown in Figure 5b.

5. Test results and analysis

5.1 Test environment set up

In this paper, the DCU of a certain car is used as the carrier, and the real car test is carried out on the real car door. The test bench is shown in Figure 6. DCU is the door controller, the programmable power supply provides 13V power supply voltage, CANcase provides the real-vehicle communication environment, the PC communicates with the DCU through the USB to CAN and controls the DCU to complete the lifting function of the window. According to industry regulations, the anti-pinch force test points are divided into three points: A, B, and C which represent the anti-pinch information on the left, middle, and right edges of the window. The test bench is composed of car windows, PC, CANcaseXL and DriveTest. The basic lifting function, combined lifting function, force measurement are controlled through host computer. Through the UDS diagnostic command to flash the control parameters to achieve the calibration of the various parameters of the car window.

5.2 Test and analysis of anti-pinch force during start-up phase

At a room temperature of 25°C and a voltage of 13V, the current and reversal threshold of the window with Freeplay and without Freeplay are shown in Figure 7. It can be seen that under the control of the Freeplay compensation strategy can follow the current changes caused by overcoming the static friction of the rope tension during the start-up phase and improve the stability of the anti-pinch control in this unstable phase. It is shown from the figure, the reversal threshold can well follow the current change caused by overcoming the static friction of the rope tension during the start-up phase.
Figure 7. The difference between the two start-up phases

The reversal of the window at point B in the Freeplay phase is shown in Figure 8a. The green line represents the position of the car window. The black line represents the normal phase reversal current threshold (Normal_limit), the blue line represents the start-up phase reverse current threshold (Startup_limit), the red line represents the actual motor current during the start-up phase and the purple line represents the normal phase current reversal threshold (I_Ext). It can be seen from the figure that the current compensation threshold in the Freeplay can follow the actual current well, when Normal_limit > I_Ext, the anti-pinch function is activated.

Figure 8. Current threshold compensation

The reversal of the window at point B without Freeplay is shown in Figure 8b. It can be seen from the figure that the starting current without Freeplay changes less drastically than in the Freeplay phase, so the compensation threshold will be smaller. At this time, if an object is pinched, the current will start to rise due to the stall. When the actual current Motor current is greater than the Start-up_limit, even if the anti-pinch threshold is still greater than I_Ext, the windows will also be reversed according to the anti-pinch strategy during the start-up phase, so as to reduce the anti-pinch force during short-distance start-up to meet the requirements of the GB11552-2009.

Table 2. Anti-pinch force table

|        | No Freeplay | Freeplay | Constant |
|--------|-------------|----------|----------|
|        | A | B | C | A | B | C | A | B | C |
| First  | 78 | 79 | 78 | 89 | 78 | 86 | 45 | 56 | 55 |
| Second | 76 | 74 | 77 | 82 | 89 | 88 | 50 | 58 | 54 |
| Third  | 78 | 76 | 80 | 87 | 87 | 84 | 47 | 53 | 52 |

It can be seen from Figure 7 that in the case of Freeplay, since the current threshold will follow the actual current value for compensation, the threshold at this phase will be larger than the threshold of No Freeplay. Since the force measurement process of the dynamometer is a spring system, the larger the
current threshold. After the window is pinched, the greater the degree of deformation of the dynamometer, and the anti-pinching force can be greater. As shown in Table 2 and Figure 8b, when measuring the constant distance anti-pinching force, since the ripple motor has been running stably, after the anti-pinching is triggered at this time, the load will increase and the current will reach the threshold faster than the start-up phase.

6. Conclusion
The purpose of this paper is to improve the anti-pinching performance of the vehicle window during the start-up phase, and analyze the physical phenomenon and current characteristics of the ripple motor during the start-up phase. On this basis, fuzzy reasoning is used to identify the starting current state of the window at this time, and the decided starting current state is used as the input of the anti-pinching control strategy, different current thresholds are set for different current states based on the Freeplay mechanism. This paper compares the anti-pinching force of Freeplay during the start-up phase with the anti-pinching force of the normal phase. It found that the Freeplay mechanism and fuzzy compensation control strategy can meet the anti-pinching force requirements of the start-up phase and the normal phase. It solves the problem that the anti-pinching force of the ripple motor easily exceeds the GB11552-2009 standard during the start-up phase.

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