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Optimized Control Technique for Power Window in Smart Car Using H Filter

S. Ramsankar, S. Paul Sathiyan

Abstract: *A practical pinch torque estimator based on the H_∞ filter is proposed for low-cost anti-pinch window control systems. To obtain the acceptable angular velocity measurements, the angular velocity calculation algorithm was proposed with the measurement noise reduction logics in previous method. Apart from the previous works based on the angular velocity or torque estimates for detecting the pinched condition, the proposed pinch detection algorithm makes use of the torque rate information integrated with state flow chart. To do this, the torque rate is augmented to the system model and the torque rate estimator is derived by applying the steady-state H_∞ filter recursion to the model. The motivation of this approach comes from the idea that the torque rate is less sensitive to the motor parameter uncertainties. Moreover, the statistics of modeling errors and angular velocity measurement noises are actually unknown. Hence, the proposed scheme minimizes the anti-pinch window control system's exposure to the false alarm. To detect the pinched condition, a systematic way to determine the threshold level of the torque rate estimates is also suggested via the deterministic estimation error analysis. Experimental results certify the pinch detection performance of the proposed algorithm and its robustness against the motor parameter uncertainties.*

Keywords: *Torque Estimation; Pinch Detection; Anti-PinchWindow Control Systems; steady-state H_∞ Filter; State flow chart.*

I. INTRODUCTION

An anti-pinch window control system associated with a motor vehicle is intended for preventing injuries when an obstacle is carelessly brought between the closing window and the door frame. Detecting a pinched condition, the window is controlled to the predetermined position. Therefore, the system performance depends on the reliability of the decision making strategy for the pinch condition. The block diagram of the anti-pinch window control system is depicted in Fig. 1.The system under consideration is operated by the on-off control method. It has a DC motor for window lift mechanism [1].

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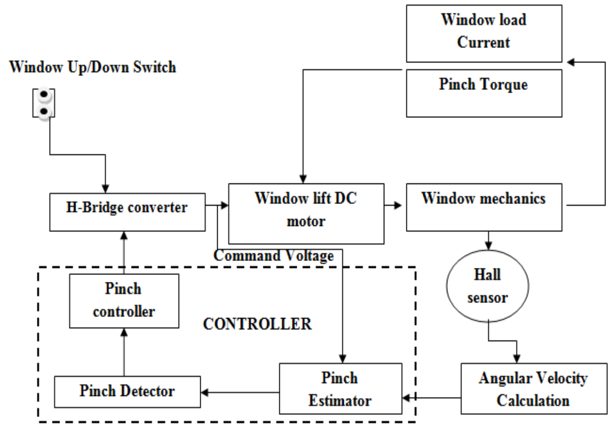

Fig.1 Anti Pinch Power window control System

The block diagram of the anti-pinch window control system is depicted in Fig. 1. The system under consideration is operated by the on-off control method. It has a DC motor for window lift mechanism [1].

The conventional methods to detect the pinched condition are generally classified into two categories: The differential type pinch estimator which is based on the assumptions that the window moves with constant velocity under the unobstructed operating condition and the abrupt drop of velocity is occurred in the pinched condition [2]. However, this algorithm could be inadequate in real situations because the frictional torque of window frame has the normally varying characteristics through the full range of power window closure panel [3]. This type of pinch estimator requires small amount of computation but its performance could be significantly degraded in the presence of measurement noises [2]. On the other hand, the absolute type pinch estimator takes advantage of the fast response time by using the changes of motor control current to compensate the pinch torque as well as the angular velocity [4-5]. It recognizes the pinched condition when the current exceeds a prescribed threshold. However, it cannot guarantee the robustness against the abnormal vibrations under the real driving conditions.

In this paper, the low-cost anti-pinch window control system, which uses only the poor angular velocity measurements from

Hall sensor, is under consideration. In this case, the pinch detection performance tends to be affected by the quality of the angular velocity measurements. Due to this reason, the conventional angular velocity calculation method is supplied with the validity verification process of the angular velocity and the impulsive noise reduction algorithm.

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Then, to overcome the limitations of the traditional methods, a new pinch detection algorithm using the torque rate estimates is proposed. The filter model includes various error sources and takes the exogenous torques into consideration. The vibration torque according to road conditions, the fluctuations of reference voltage and the measurement noises are modeled by energy bounded disturbances. Especially, to deal with the time varying nature of the frictional torque which is proportional to window travels, an augmented motor model with the torque rate state is suggested. Since the torque rate estimate is free from the bias errors due to the motor parameter variations and has relatively fast rising time, the proposed method can provide satisfactory pinch detection results with high fidelity. In addition, by analyzing the influence of the motor parametric uncertainties on the estimation errors, a systematic way to determine the threshold level of torque rate at pinched condition is introduced. Experimental results show the pinch detection performance and robustness of the proposed method.

II. H FILTER BASED PINCH TORQUE ESTIMATION

A. State-Space Model for Pinch Torque Estimation

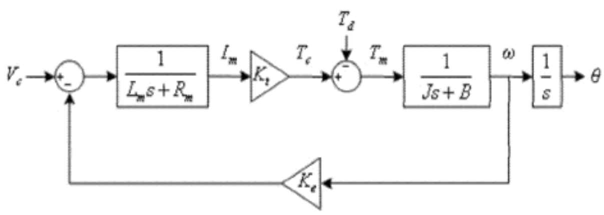

Fig. 3. Linearized motor model

As shown in the Fig. 3, the DC motor system to drive window can be linearized by neglecting the nonlinear characteristics such as backlash, slew-rate, coulomb friction, etc. The nomenclature list of the linearized motor model is given below:

V_c	Driving voltage
ω	Angular velocity
θ	Angular position
I_m	Armature current
L_m	Armature inductance
R_m	Armature resistance
J	Motor inertia
B	Viscosity friction coefficient
K_e	Back electromotive force co efficient
K_t	Torque coefficient
T_c	Control torque
T_d	Disturbance torque
T_m	Rotational Torque

From Fig. 3, the transfer function from the rotational torque of a DC motor to the angular velocity is given by

$$\frac{\omega(s)}{T_m(s)} = \frac{1}{Js+B} \tag{1}$$

The rotational torque is subdivided into the control torque T_p, pinch torque T_p by the obstacle and the load torque T_w, by the window weight.

$$T_m = T_c - T_d = T_c - T_p - T_w - T_v \tag{2}$$

Since the vibration torque T, varies along the road conditions,
it is not easy to model. The velocity variation due to the vibration torque is assumed as unknown but bounded exogenous noise u, without loss of generality. From (1) and (2), the motor speed holds the dynamics equation

$$\dot{\omega} = -\frac{B}{J}\omega + \frac{1}{J}T_c - \frac{1}{J}(T_p + T_w) + u_v \tag{3}$$

Using the fact that the electrical dynamics of the motor is much faster than the mechanical one, the motor control torque can be approximated as follow:

$$T_c \approx \frac{K_t}{R_m}(V_c - K_e w) \tag{4}$$

Substituting (4) for (3) yields

$$\dot{\omega} = -\left(\frac{B}{J} + \frac{K_t K_e}{J R_m}\right)\omega - \frac{1}{J}(T_p + T_w) + u_v + \frac{K_t}{J R_m}V_c \tag{5}$$

The magnitude of a window load torque T_w is nearly proportional to the window position. On the contrary, the pinch torque T_p appears abruptly at the pinched moment and the pinch torque profile can be changed by the types of pinched obstacles. The practical window load and pinch torques are shown in the Fig. 4. In general, the magnitude of the window load torque is smaller than the pinch torque except at the end of window aperture. Moreover, at the pinch moment, the rate change of torque is distinguished from the condition that the pinch force is absent. Therefore, it is more effective to model these torques as a single state variable for the pinch estimator.

$$T = T_p + T_w \tag{6}$$

The exogenous torque (8) which is closely related to the pinched condition is considered as a deterministic input to be estimated. As shown in the Fig. 4, both of exogenous torques T_w, and T_p could be approximated as ramp functions with proper slopes. In this case, one of simplest ways to detect the pinched condition is to monitor the slope of exogenous torque T.Actually, the torque rate is increased much faster than the torque. This implies that the pinch detection method using the torque rate estimate could be effective in many cases. Furthermore, since the motor parametric uncertainty causes

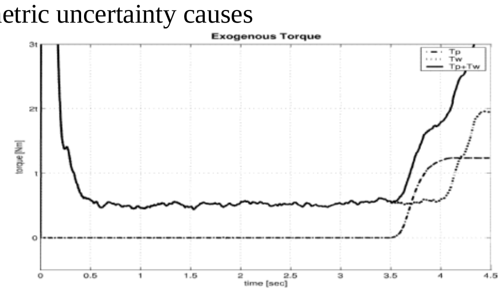

Fig. 4. Pinch torque and window load torque

the bias error in the filtered torque estimate, the previous pinch detection algorithm based on the torque estimate only might not be suitable to the practical applications.

To solve the problem, the torque rate T is augmented as an additional state and modeled by a random walk using the energy bounded noise sequence u_{TD} as follows

$$\dot{T} = u_{TD} \quad (7)$$

Now, from (5), (6) and (7), one can have the state-space model (8) for the pinch estimator

$$\dot{x} = Fx + G_c V_c + Gu$$

$$y = Hx + v \quad (8)$$

where y is the angular velocity measurement mentioned before and

$$x = [\omega \quad T \quad \dot{T}]^T, \qquad u = [u_v \quad u_{TD}]^T$$

$$F = \begin{bmatrix} -\frac{B}{J} - \frac{K_t K_e}{JR_m} & -\frac{1}{J} & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{bmatrix} \quad G_c = \begin{bmatrix} \frac{K_t}{JR_m} \\ 0 \\ 0 \end{bmatrix}$$

$$G = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix}^T \quad H = [1 \quad 0 \quad 0]$$

Since there is no statistical information on the exogenous noises u and v, to design the pinch estimator, the H_∞ filtering algorithm is more attractive than the conventional Kalman filter.

B. *Pinch Estimator using the H_∞ Filter*

After the discretization of the continuous system model (8), one gets the discrete-time state-space equation of the form

$$x_{k+1} = \Phi x_k + \Gamma_c V_c + \Gamma u_k$$

$$y_k = Hx_k + v_k \quad (9)$$

where the matrices are defined by using the sampling time T_s
of the filter.

$$\Phi = L^{-1}(sI - F)^{-1}|t = T_s$$

$$\Gamma_c = \int_0^{T_s} \Phi(T) G_c dt$$

$$\Gamma = \int_0^{T_s} \Phi(T) G dt$$

Also, the performance output z_k is defined by the linear combination of the states to be estimated.

$$z_k = Lx_k$$

where L is an arbitrarily chosen matrix. In the filter model (9), the fluctuation of driving voltage is neglected so that the input voltage is assumed as constant. Then the pinch estimator can be designed by applying the discrete-time H_∞ filter recursion to the system equation (9).

(Measurement update)

$$\hat{x}_{k|k} = \hat{x}_{k|k-1} + K_{f,K}(y_k - H\hat{x}_{k|k-1})$$

(10)

$$P_{k|k} = P_{k|k-1} - (P_{k|k-1}\tilde{H}^T R_e^{-1} \tilde{H} P_{k|k-1})$$

(11)
Where,

$$R_{e,k}^{-1} = \tilde{R} + \tilde{H} P_{k|k-1} \tilde{H}^T$$

$$\tilde{H} = \begin{bmatrix} H \\ L \end{bmatrix} \quad \tilde{R} = \begin{bmatrix} 1 & 0 \\ 0 & -\gamma^2 I \end{bmatrix}$$

and the H_∞, filter gain $K_{f,k}$ is defined by

$$K_{f,k} = \left(P_{k|k}^{-1} + \gamma^{-2} L^T L\right)^{-1} H^T$$

(12)

(Time update)

$$\tilde{x}_{k+1|K} = \Phi \tilde{x}_{k|k} + \Gamma_c V_c$$

(13)

$$P_{k+1|k} = \Phi P_{k|k} \Phi^T + \Gamma \Gamma^T$$

(14)

where $P_{k|k-1}$ and $P_{k|k}$ are the a priori and a posteriori estimation error covariance matrices. It has been also assumed that the H_∞ norm bound, γ, is given. Taking account of the real-time implementation issue, the steady-state H_∞, filter gain is used.

$$K_f = (P_\infty^{-1} + \gamma^{-2} L^T L)^{-1} H^T$$

(15)

From the equations (11) and (14), the steady-state error covariance matrix P_∞ holds the following discrete-time algebraic Riccati equation.

$$0 = \tilde{P}_\infty - P_\infty - \tilde{P}_\infty \tilde{H}^T (\tilde{H} P_\infty \tilde{H}^T + \tilde{R})^{-1} \tilde{H} \tilde{P}_\infty$$

(16)

Where,

$$\tilde{P}_\infty = \Phi P_\infty \Phi + \Gamma\Gamma^T$$

III. DECISION OF PINCHED CONDITION

In this section, the estimation error due to the parametric uncertainties in the motor model is analyzed. The results give us new insights into the validity of the torque rate estimates for pinch detection. The parametric uncertainties of motor model are able to generate the biased torque estimates. To facilitate the error analysis, the noise sources are ignored and the steady-state H_∞ filter for the continuous time motor system (8) is considered.

$$\dot{\hat{x}} = (\bar{F} - K_f H)\hat{x} + K_f \omega + \bar{G}_c V_c$$

(17)

Where,

$$\bar{F} = \begin{bmatrix} -\frac{B}{J} - \frac{\bar{K}_t \bar{K}_e}{JR_m} & -\frac{1}{J} & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{bmatrix} \quad \bar{G}_c = \begin{bmatrix} \frac{\bar{K}_t}{JR_m} \\ 0 \\ 0 \end{bmatrix} \quad K_f = \begin{bmatrix} K_\omega \\ K_T \\ K_{\dot{T}} \end{bmatrix}$$

In the above equation, X means the uncertain parameter or matrix corresponding to the nominal one X. From (5) and (17), the error system (18) can be obtained.

$$\dot{z} = Az + B_c u_c$$

$$e_{\dot{T}} = \dot{T} - \hat{\dot{T}} = \dot{T} - C_z$$

(18)
Where,

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$$A=\begin{bmatrix} -\frac{B}{J}-\frac{K_tK_e}{JR_m} & 0 & 0 & 0 \\ K_\omega & -\frac{\bar{B}}{J}-\frac{\bar{K}_t\bar{K}_e}{JR_m}-K_w & -\frac{1}{J} & 0 \\ K_T & -K_T & 0 & 1 \\ K_{\dot{T}} & -K_{\dot{T}} & 0 & 0 \end{bmatrix} \quad B_c=\begin{bmatrix} \frac{K_t}{JR_m} & -\frac{1}{J} \\ \frac{\bar{K}_t}{JR_m} & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \quad C=\begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix}^T$$

$$z=\begin{bmatrix} \omega \\ \hat{\omega} \\ \hat{T} \\ \hat{\dot{T}} \end{bmatrix} \qquad u_c=\begin{bmatrix} V_c \\ T \end{bmatrix}$$

For the simplicity, the driving voltage is assumed as a step input. The window load torque and pinch torque are regarded as ramp inputs for calculating the torque rate estimation error, since the step inputs result in the zero steady-state estimation error. On the other hand, they are considered as step inputs to obtain the steady-state torque estimation error because the ramp inputs make the error diverge. According to the final value theorem, the steady-state estimation errors can be readily derived.

$$e_{\dot{T}}(\infty)=\left(1-\frac{\bar{R}_m(K_tK_e+R_mB)}{R_m(\bar{K}_t\bar{K}_e+\bar{R}_m\bar{B})}\right)(a_w^r+a_p^r) \tag{19}$$

$$e_{\dot{T}}(\infty)=\left(1-\frac{\bar{R}_m(K_tK_e+R_mB)}{R_m(\bar{K}_t\bar{K}_e+\bar{R}_mB)}\right)(a_w^s+a_p^s)+\left(\frac{K_t}{R_m}-\frac{\bar{K}_t(K_tK_e+R_mB)}{R_m(\bar{K}_t\bar{K}_e+\bar{R}_m\bar{B})}\right)V_c \tag{20}$$

where a^r_w and a^r_p are the slopes of the window load and pinch torques. Also, a^s_w and a^s_p are the magnitudes of the torques. From equ(19) and equ(20), it is obvious that parametric uncertainties directly affect to the torque and torque rate estimates. However, it causes larger bias errors to the torque estimates.

IV.STATE FLOW CHART CONCEPT

State flow is a graphical design and development tool control and supervisory logic used in conjunction with simulink.In provides clear, concise descriptions of complex system behavior using finite state machine theory, flow diagram notation, and state-transition diagrams all in the same state flow diagram as described in the topics

- State flow is a finite state machine
- State flow Adds Flow Diagram to the state machine
- State flow simulates its state machine
- State flow generates code

State flow automatically generates integer, floating-points, or fixed-point code directly from our design

A.Modules in control flow:

- ❖ Validate Driver
- ❖ Validate Passenger
- ❖ Detect Obstacle End stop

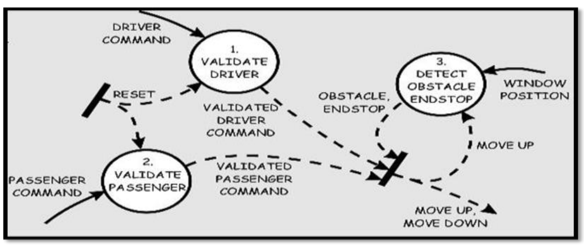
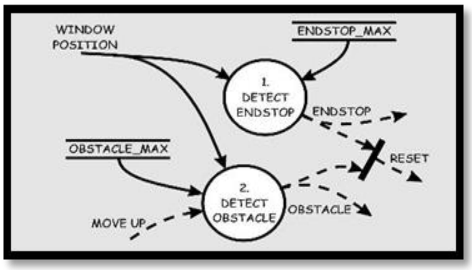


Fig. 5 Power windrow control by validation

The power window control consists of three processes and a CSPEC. Two of the processes validate the driver and passenger input to ensure their input is meaningful given the state of the system (e.g., if the window is completely opened, the 'window down' command is not sensible). The remaining process detects whether the window is completely opened or completely closed and whether an object may be present. The CSPEC takes the control signals and infers whether the window should be moved up or down (e.g., if an object is present, the window should be moved down for about one second or until an endstop is reached).

B.Detect Obstacle End-stop

The third process in the POWER WINDOW CONTROL activity diagram is the one to detect the presence of an obstacle or when the window reaches its top or bottom ('endstop'). The detection mechanism is based on the armature current of the window actuator. During normal operation, this current is within certain bounds. When the window reaches its top or bottom, the electro-motor draws a large current (more than 15 [A] or less than -15 [A]) to try and sustain its angular velocity. Similarly, during normal operation the current is about 2 [A] or -2 [A] (depending on whether the window is opening or closing). When an object is present, there is a slight deviation from this value. To ensure the window force on the object is less than 100 [N], the control switches to its emergency operation when a current is detected that is less than -2.5 [A] (this is only necessary in case the window is rolling up, which corresponds to a negative current in the particular wiring of this model). This functionality is embodied by the DETECT OBSTACLE ENDSTOP activity diagram and the process specifications given in Fig.5.



V.EXPERIMENTAL RESULTS

The performance of the steady-state H_∞ filter based pinch detection algorithm has been evaluated by experiments For experiments, the sampling time is selected as 1 msec. During the filter convergence time, 0.5 sec, the pinch detection algorithm does not work. Also, the Hm, norm bound $_\gamma$ is chosen as 1.002. The two kinds of pinch forces are applied to the window by the springs which have different spring rates, 20 N/mm and 65 N/mm. As shown in the figures, the angular velocities are abruptly reduced at the pinched moments and, accordingly, the torque rate estimates suddenly increase when the pinched torque is applied.

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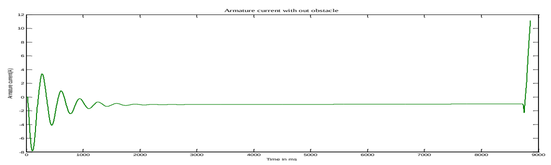
Test results indicate that the pinched conditions can be successfully detected using the predetermined threshold level of torque rate estimates. That is, if the estimated torque rate is over the threshold, we can make decision for taking precautions. can see that the pinched condition is successfully detected at the about 0.07 sec after the pinch torque has appeared.

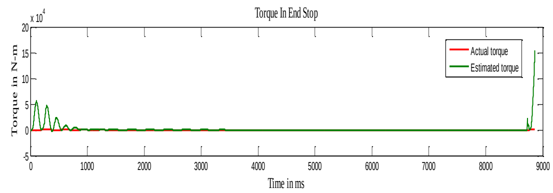
Considering the previous detection method using the changes of armature current requires [2] 0.17 sec for pinch protection, it is remarkable improvement in the response time. Regardless of the elasticity degree of a pinched obstacle, the proposed method detects the pinched condition relatively fast. As well, in spite of the severe noises in angular velocity measurements, it provides consistent pinch detection performances.

Using the simulation program of the anti-pinch window control system, the performance of the proposed estimator is compared to that of the conventional disturbance torque estimators. Especially, to observe the influence of the parametric uncertainty, it is assumed that the torque constant K_t allows the -10% error of its nominal value.

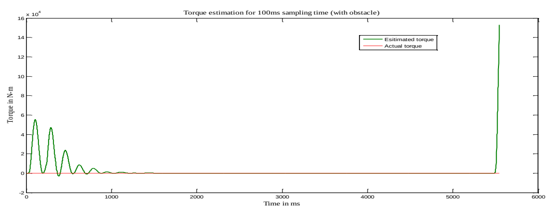
From the table.1 it is clear that the proposed system has fast response time.

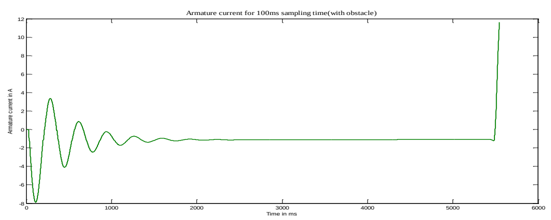
AT 100ms SAMPLING TIME



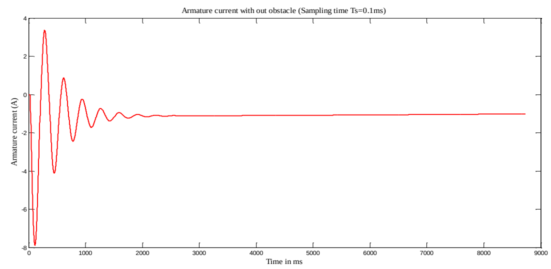


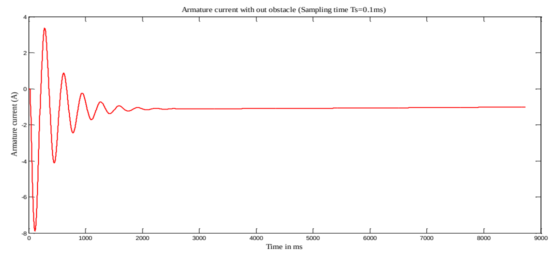
WITH OBSTACLE:



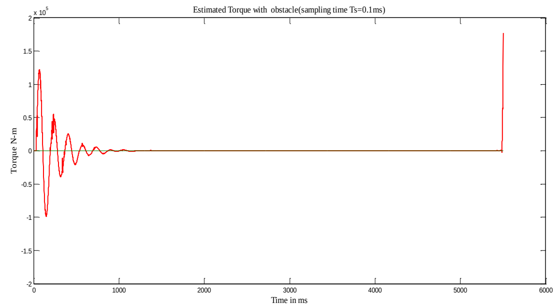


AT 0.1ms SAMPLING TIME





WITH OBSTACLE STOP:



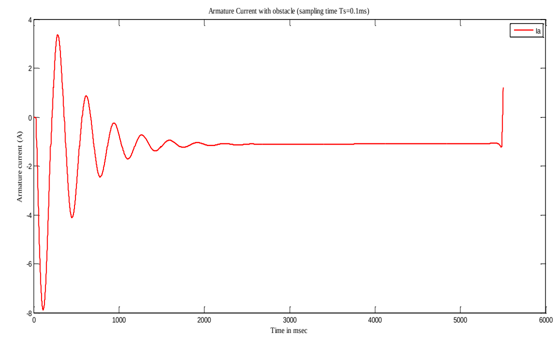


Table.1 Response time

Sampling time	End stop Response time	Obstacle stop Response time
100ms	120ms	56ms
50ms	106ms	36ms
10ms	1ms	21ms
1ms	0.5ms	14ms

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VI.CONCLUSION

In this paper, a new pinch torque estimation algorithm based on the H_∞ filter has been proposed. To prevent the performance degradation of the pinch estimator due to the noises, an accurate angular velocity detection was considered. Moreover, by considering the torque rate as an additional state variable, the proposed method could improve the reliability for the pinch detection even in the presence of the parameter uncertainties. In addition, the results of estimation error analysis were given to derive the threshold level of torque rate estimates at the pinched condition. Therefore, it can be said that the proposed scheme provides the systematic way to solve the pinch detection problem. Furthermore, the proposed algorithm was preferred for real-time implementation by adopting the steady-state H_∞ filter gain. Simulation results have shown that the proposed algorithm guarantees the robust pinch detection performances. Thus, it will be a practical solution for the design of a low-cost anti-pinch window control system.

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