RESEARCH ARTICLE

(Smart Pinch Detection for Car's Electric Sunroof Based on Estimation and Compensation of System Disturbance

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Abstract: To solve the problems of internal and external disturbances caused by mechanical wear, electrical aging and complex road conditions, a practical and robust pinch detection algorithm is proposed for the anti-pinch control systems of the car's sunroof. The proposed algorithm makes use of grey theory to predict and compensate the uncertain disturbances. To detect electric sunroof pinch state, a kind of torque rate is selected as the observation state due to the less sensitivity of the torque rate to the uncertainty of the motor's parameters and supply voltage than the torque or the angular speed. The torque rate is obtained by using angular velocity measurements calculated from the Hall sensor output. To detect the pinched condition, a systematic way to determine the threshold level of the torque rate estimation is also suggested. The experimental results show that our method meets the requirements of European Directive 74/60/ECC, China GB 11552-2009 and America Directive FMVSSll8,and has excellent performances in detecting car's electric sunroof pinch state.

Keywords: Electric sunroof, grey theory, smart pinch detection, state estimation, vehicular safety systems

1. Introduction

Recently the Electric sunroof is widely used in the car because the automatically opening and closing of the sunroof brings convenient operations and can meet various needs. But the more important problem of the intelligent car sunroof lies in the convenience and safety of vehicle occupants, passengers, and pedestrians [1-3]. As one of the important electronic control units, the electric sunroof system must be sa designed with safety because it is often possible to injure people. There are numerous reports of accidents caused by car sunroof systems and other components [4] because of safety protection failure or no safety precautions. For this reason, safety regulations such as European Directive 74/60/ECC, China GB 11552—2009 and America Directive FMVSSll8 are proposed to ensure the safety of passengers. In addition, the growing demand for car sunroofs in automotive applications has also prompted the development of highly efficient safety protection systems [5-6]. To meet the safety specification, a lot of scholars have worked on the robust and accurate sunroof control system that detects pinch conditions so as to protect passengers from getting pinched.

The previous pinch detection can be divided into three categories generally. The first category is to estimate the motor velocity to judge whether there are obstacles that cause pinches [7]. However, this method may be inadequately accurate in real situations because the frictional torque and vibrational torque are not considered [8]. Moreover, its per-

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formance could be seriously influenced in the presence of measurement noise [7]. The second category is using the changes of motor control current to compensate the pinch torque as well as the angular velocity [9-10]. This method recognizes the pinched condition in the circumstances that the current exceeds a prescribed threshold [11]. But this method cannot guarantee the safety and robustness against the abnormal vibrations under the complex road conditions. Going further, this method needs an additional current sensor [12-13]. In addition, it could not be a general method because the detection of pinched threshold mostly depends on the machine and electrical design [7-8]. The last category is to use the filter to deal with the observation signal and then calculate the torque rate [6, 14]. The motivation for this approach comes from the idea that the torque rate is less sensitive to motor parameter uncertainty than the torque or the angular velocity [6]. To weaken the impact of the noise on pinch detection, some researchers proposed H∞ filter to address system noise [15-17], and other researchers proposed Kalman filter to deal with system noise [18-21]. But H∞ filter does not guarantee that the estimation error variance is minimum or in a limited range. Kalman filter works best only when the statistical characteristics of the actual input signals is consistent with the prior information of the design filter.

The electric sunroof works in a complex working condition with variations of velocity, temperature, moisture and operating voltage [22]. In addition, the obstacles like the passenger's neck or arms are soft while the mechanism structure of the sunroof is hard. In this condition, the sunroof motor's state changes are not obvious in the initial stage of the pinch. Moreover, the most important factor is the vibration of car's body in the course of driving. All these factors have brought great difficulties to the pinch detection. The detection of the sunroof pinch state is not difficult from the perceptive perspective in principle, but to design an effective and reliable anti-pinch algorithm needs a careful consideration of all the above factors. Some anti-pinch algorithms have played a certain role by using H∞ filter or Kalman filter to eliminate disturbances, but they are poor in giving correct detecting pinch state in all disturbance cases. It is obvious that, the reliability of the algorithm lies in the elimination of all kinds of interference.

In order to realize smart pinch detection, this study is to be based on grey theory, an effective way to deal with system's uncertain disturbance [23-25]. It needs less information and computational complexity, but is highly effective and easy to design. As grey theory has an advantage in dealing with uncertain disturbance system, and the torque rate is less sensitive to motor parameters uncertainty than the torque or the angular velocity, this paper adopts grey theory for the estimation and compensation of sunroof system disturbance to design a smart anti-pinch controller so as to guarantee that the pinch detection is effective and reliable.

2. Modeling of sunroof motor

The sunroof system consists of electric control unit (ECU), DC motor, sunroof glass, hall sensors, as shown in Fig.1, among all of which DC motor is the most important part for modeling the electric sunroof system.

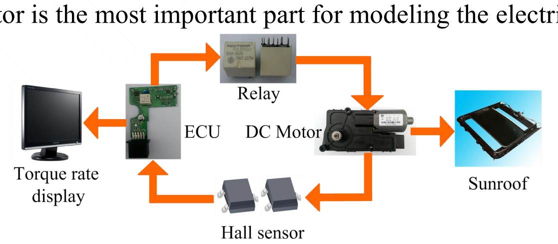


Figure 1, The structure of sunroof control system

The Hall DC motor is widely adopted to go with the car sunroof motor, namely, an ECU is embedded in the DC motor and two hall sensors are fixed in the ECU. In addition, a magnetic ring is arranged on the rotating shaft of the DC motor corresponding to the position of hall sensors. When the motor rotates, the ECU can determine the position of the sunroof and the torque rate of the sunroof motor by detecting the hall signal received by hall sensors. The DC motor has two important balance equations, the first being voltage balance equation, and the other torque balance equation.

2.1 Voltage Balance Equation

The sunroof motor input voltage is subdivided into induced electromotive force, armature resistance voltage, and inductance voltage, which can be described as follows:

$$U(t) = E(t) + RI(t) + L\frac{dI}{dt} \tag{1}$$

In the DC motor voltage balance equation, U refers to input voltage, E refers to induced electromotive force, I refers to armature current, and L refers to armature inductance. The relationship between the induced electromotive force and the angular speed of the motor is shown as the following equation:

$$E(t) = k_e\omega(t) \tag{2}$$

In the above equation k_e refers to induced electromotive force coefficient, ω refers to motor angular speed.

2.2 Torque Balance Equation.

The relationship between the electromagnetic torque and load torque, pinch torque and the angular speed of the motor is shown in the following equation:

$$T_m(t) - B\omega(t) = J\frac{d\omega(t)}{dt} \tag{3}$$

In the DC motor torque balance equation, B refers to viscous friction constant, J refers to moment of inertia, and T_m refers to rotational torque. It comes from control torque T_c.

In the process of pinching, the torques' relationship is shown in the following equation:

$$T_m(t) = T_c(t) - T_d(t) = T_c(t) - T_p(t) - T_v(t) - T_w(t) \tag{4}$$

In the above equation, T_p refers to pinch torque, T_w refers to load torque, and T_v refers to vibrational torque. The relationship between T_c and armature current is shown as the following equation:

$$T_c(t) = k_t I(t) \tag{5}$$

In equation (5), k_t refers to torque constant.

The above equations can be described by Fig. 2.

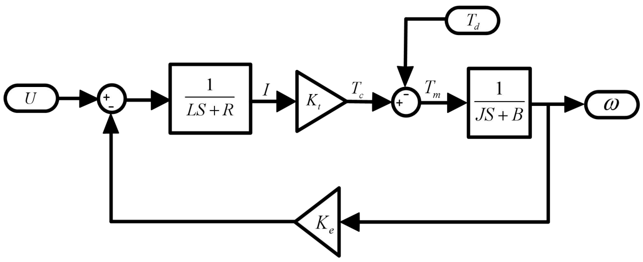


Figure 2, The model of sunroof motor

Disturbance estimation

In this section, the grey theory is used to estimate electric sunroof system disturbances. First, the grey sunroof system is introduced, and then the grey model to estimate system disturbances is presented with six steps. With these six steps, the sunroof system disturbances can be estimated reasonably.

Grey System of Sunroof

The grey theory mainly adds the observation sequence, and then transforms the original discrete series of chaos into the increment series. Using the grey theory to model the grey system can obtain a certain degree of transparency of the system, so as to facilitate state estimation and real-time control. A general nonlinear grey system composed of N state variables can be expressed as follows:

$$\dot{x} = Ax(t) + Bu(t) + Bw(x,t) \tag{6}$$

In the above equation, $x \in R^n$, $u \in R$, A is n×n matrix, B is n dimension matrix, $w(x,t) \in R$. Assuming that the uncertain part meets the conditions, which can be described as Bw(x,t). w(x,t) represents the uncertain disturbances to meet the conditions. It contains parameters uncertainty and external disturbance. How to estimate and compensate the w(x,t) is a difficult problem in the field of control and state estimation. w(x,t) can be expressed as the following equation:

$$w(t) = V_1x_1 + V_2x_2 + ...+ V_nx_n + f(t) \quad (7)$$

In the above equation, V=(V1,V2……,V_n) relates to system state variables. But it can't be measured accurately. f(t) is an independent part disturbance of the system, for example, the electromagnetic interference from other electromagnetic unit in car body. f(t) can be expressed as follows:

$$f(t) = f_0\delta(t) \quad (8)$$

In equation (8) the value of $\delta(t)$ can be seen as a constant value. Thus, to estimate the uncertain disturbances, it only estimates the parameters of $V_w=[V_1, V_2, \dots V_n, f_0]^T$.

In electric sunroof system, the state variables like armature current and angular speed of the sunroof motor can be measured with on-board sensors. However, due to the change of temperature, humidity of the environment, sunroof service life extension and uncertain vibration in the running process, the direct measured values of armature current and angular velocity with on-board sensors are not accurate. Due to this reason, the values of armature current and angular velocity need to be obtained by estimation method so as to eliminate the internal and external disturbances. To estimate the internal and external disturbances, the state space model of sunroof need to be built to construct grey model. According to the equation (1), (3), selecting x_1=I, x_2=ω as the state variables, the state space model of electric sunroof system is established as follows:

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = A\begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + B\begin{bmatrix} U \\ T_d \end{bmatrix} + Bw(x,t) \quad (9)$$

where:

$$A = \begin{bmatrix} -\frac{R}{L} & -\frac{C_e\Phi}{L} \\ \frac{C_t\Phi}{J} & \frac{\mu}{J} \end{bmatrix}, \quad B = \begin{bmatrix} \frac{1}{L} & -\frac{1}{J} \end{bmatrix}.$$

To obtain the accuracy states of x_1 and x_2 in equation (9), it is obvious that the w(x,t) needs to be estimated with good accuracy. To address this problem, the next sub-section will use the grey theory to estimate the w(x,t).

Disturbance Estimation Based on Grey Theory

The uncertain disturbances cannot be directly measured, but it can be estimated indirectly by measuring the measured data based on the grey theory. From equation (8) comes the following relationship:

$$w(t) = \frac{1}{B}(\dot{x}(t) - Ax(t) - Bu(t)) \quad (10)$$

In the above equation, t=KT, T is the sampling time. The steps of grey theory to estimate the disturbances are as follows:

Step1: Obtaining the original discrete sequence of $x_i^{(0)}(k)$, which can be expressed as follows:

$$\begin{cases} x_1^{(0)}(i) = x_1(i) \\ x_2^{(0)}(i) = x_2(i) \end{cases} \quad (11)$$

Step2: Obtaining the cumulative discrete series of the original sequence by following the rule in (12):

$$\begin{cases} x_1^{(1)}(i) = \dfrac{x_1^{(0)}(i-1) + x_1^{(0)}(i)}{2} \\ x_2^{(1)}(i) = \dfrac{x_2^{(0)}(i-1) + x_2^{(0)}(i)}{2} \end{cases} \quad (12)$$

Step3: Constructing the matrix B_b according to the cumulative discrete series in (12), and it can be expressed as follows:

$$B_b = \begin{bmatrix} x_1^{(1)}(2) & x_2^{(1)}(2) & 1 \\ x_1^{(1)}(3) & x_2^{(1)}(3) & 2 \\ \cdots & \cdots & \cdots \\ x_1^{(1)}(N) & x_2^{(1)}(N) & N \end{bmatrix} \tag{13}$$

In the above matrix, $B_b^T B_b$ must be reversible. If $B_b^T B_b$ is not reversible, it needs to appropriately increase the size of N, until the matrix $B_b^T B_b$ can be reversible.

Step4: Calculating the discrete sequence of w according to the original state sequence $x^{(0)}(k)$ and the equation (9).

$$w^{(0)} = (w(0),\ w(1) \ldots w(N)) \tag{14}$$

Step5: Obtaining the cumulative discrete series of the $D^{(1)}(k)$ by following the rule in (15):

$$D^{(1)}(i) = \frac{w(i-1)+w(i)}{2} \tag{15}$$

Step6: Estimating the parameters value of $V_w=[V_1, V_2, \ldots V_n, f_0]^T$, which can be shown as follows.

$$\hat{V}_w = (B_b^T B_b)^{-1} B_b^T D^{(1)} \tag{16}$$

According to the estimated results in (16), we can obtain the uncertain disturbances. It can be expressed as follows:

$$\hat{w}(i) = \hat{V}_w \times [x_1, x_2, \delta(t)] \tag{17}$$

By the above steps, the uncertain disturbances can be estimated.

Pinch Detection Design

This section presents a new electric sunroof pinch detection method. The judgment of pinch state vector is first designed, and the pinch detection threshold is derived by referring to the existing safety regulation. Then the pinch detection method is proposed with compensation system disturbances.

Pinch State Selection and Threshold Design

From equation (2), the following equation can be obtained:

$$T_p(t) - T_w = T_c(t) - J\frac{d\omega(t)}{dt} - \mu\omega(t) - T_v(t) \tag{18}$$

In the above equation, the rotating angular velocity of the motor can be obtained through the hall sensor. Thus, the torque of T_c can be obtained according to the value of rotating angular velocity. In complex road conditions, the vibration torque T_v varies along with road conditions, and it is neither a lasting nor a transient dominant disturbance to the motor. So it is not easy to model the nature of T_v precisely. But T_v has a great influence on the detection of pinch state, and it is very easy to cause wrong judgment or missing judgment. So it will not be negligible as to the influence of T_v in the process to accurately detect the pinch state. Some algorithms using Kalman filter to reduce the impact of T_v on the process of pinch detection, but it does not have a good effect on all kinds of disturbances though it can produce a certain effect. To make the grey theory easily used to eliminate the sunroof system disturbances, all kinds of torques need to be analyzed in detail. Based on the laboratory experiments, T_w remains almost unchanged, but T_p and T_c appear abruptly at the pinching moment, which can be shown in Fig.3. Therefore, the following torque can be reasonably selected as the detection torque.

$$T = T_p + T_w = k_t I_d - J\dot{\omega} - \mu\omega - T_v \tag{19}$$

From (19) it can be known, if the vibrational torque T_v can be reasonably estimated, then the pinch state can be accurately detected.

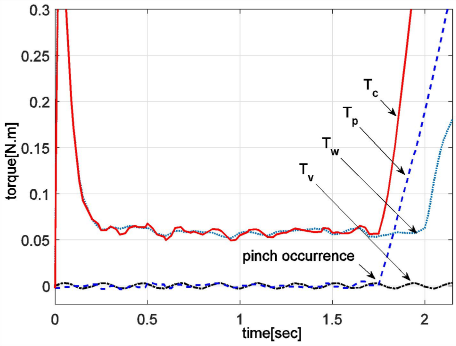


Figure 3, All torques in the pinch process

Due to the severe working environment of the sunroof, the changes of temperature, humidity and mechanical wear have great influence on the parameters of the sunroof motor, which will result in a great influence on the detection torque. But the torque rate is almost not affected by the above factors, so the torque rate is an effective way of detecting the pinched condition. In order to reasonably detect the pinch condition, a remaining important problem is selecting a reasonable torque rate threshold level to determine the pinch state. Normally, the DC motor manufacturer maintains the parameter variations within ±10% of the nominal values. Therefore, the boundary of the torque rate estimation can be regularized according to the literatures [19-21].

$$\hat{\dot{T}} \geq \min(0.74\hat{\dot{T}}) = \min(\hat{\dot{T}}_p + \hat{\dot{T}}_w) \tag{20}$$

Pinch Detection Based on Disturbance Compensation

In this section, the sunroof pinch detection based on disturbance compensation is designed to detect pinch state. Similar to literatures [6, 14, 21], it is appropriate to model the $\dot{\omega}(t)$ as a random walk using the zero-mean white noise input $u_{\dot{\omega}}$ with the variance $Q_{\dot{\omega}}$

$$\ddot{\omega}(t) = u_{\dot{\omega}} \tag{21}$$

From (1), (3), (4) and (21), a state-space equation can be built as follows:

$$\dot{\hat{x}} = F\hat{x} + G_c u_c + Gw \tag{22}$$

where

$$F = \begin{bmatrix} -\frac{R}{L} & -\frac{K_e}{L} & 0 \\ \frac{K_t}{J} & -\frac{\mu}{J} & 0 \\ 0 & 0 & 0 \end{bmatrix}, \quad G_c = \begin{bmatrix} \frac{1}{L} & 0 \\ 0 & -\frac{1}{J} \\ 0 & 0 \end{bmatrix}, \quad G = \begin{bmatrix} 0 & 0 \\ -\frac{1}{J} & 0 \\ 0 & 1 \end{bmatrix},$$

$$u_c = \begin{bmatrix} u \\ T \end{bmatrix}, \quad w = \begin{bmatrix} T_v \\ u_{\dot{\omega}} \end{bmatrix}, \quad H = [0 \quad 0 \quad 1], \quad x = [\hat{i}, \hat{\omega}, \hat{\dot{\omega}}]^T.$$

According to (20) and (22); the pinch detection torque rate can be obtained as follows:

$$\hat{\dot{T}} = \hat{\dot{T}}_p + \hat{\dot{T}}_w = k_t \hat{\dot{I}}_d - \mu\hat{\dot{\omega}} - J\hat{u}_{\dot{\omega}} - \hat{\dot{T}}_v \tag{37}$$

Now, the car's electric sunroof pinch state can be detected by the torque rate of $\hat{\dot{T}}$

3. Experiments and Analysis

Experimental Platform

To verify the Grey-Theory-based pinch detection algorithm proposed in this paper, a general car's electric sunroof platform is selected, as shown in Fig.4. The experimental system consists of sunroof, DC motor, DC power, display device, oscilloscope and button, as shown in Fig.4. In the experiment platform, the DC motor parameters are shown in Table 1.

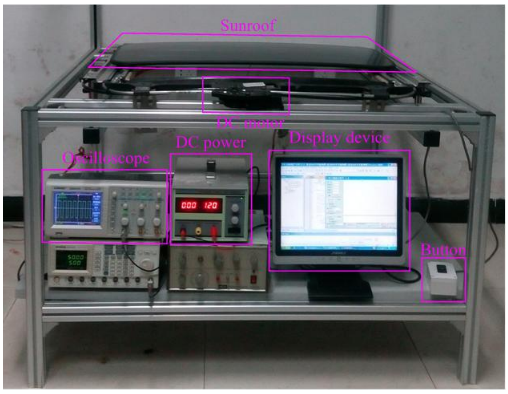


Figure 4, Car's electric sunroof platform

Symbol	Values	Unit
U	12	V
I(∞)	2.65	A
ω(∞)	426	rad/s
L_d	0.0163	H
R_d	0.6	Ω
K_e	$2.44\times10^{(2}$	V/rad/s
K_t	$2.44\times10^{(2}$	N.m/A
J	$1.3\times10^{(4}$	$Kg.m^2$
B	2.26×10^{-5}	$kg.m^2/s$

Table.1 Nominal values of the motor parameters

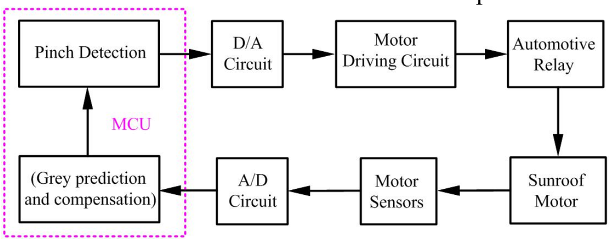


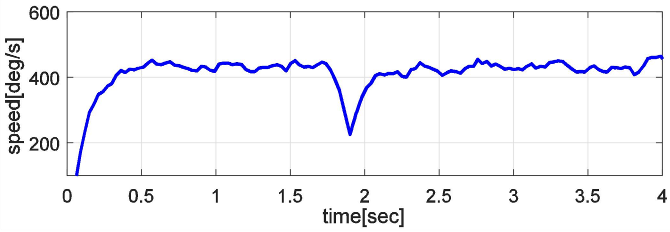
Figure 5. Sunroof real-time control system for examining pinch detection

For experiments in Fig.5, the sampling time is selected as 1ms. In the test process, the motor rotational speed and the armature current are measured with motor sensors, and this information is sent to MCU through A/D circuit. The sunroof system disturbances are first estimated with grey theory in MCU, and then compensation of the detection torque rate is made to achieve electric sunroof pinch detection. If the sunroof system comes into pinch occurrence, MCU will send command to the motor drive device so as to realize anti-pinch function. The response curve of the experiment process is displayed through a screen device. To verify the pinch detection performance, different tests are conducted with details compared with Kalman filter. In order to determine the pinch threshold of torque rate, the repeated pinched experimental tests are conducted. According the condition in (20), the reasonable pinch detection threshold of the torque rate is 0.88 [N·m/s].

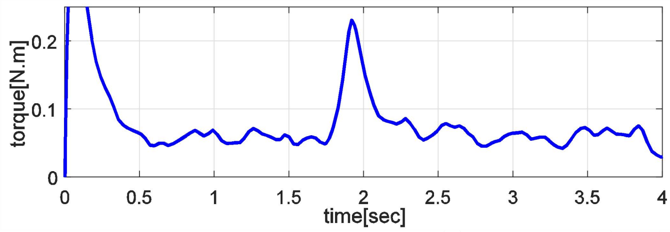
Pinch Detection under Normal Conditions

In order to test the normal condition, we set the input voltage with 12V and the model parameters this the designed parameters shown in Table .1. We tested the proposed pinch detection algorithm compared with Kalman in detail, and the results are shown in Fig. 6. Fig. 6(a) reflects the motor rotational speed during the pinch process and Fig. 6(b) reflects the motor torque during the pinch process. It can be known that the rotational speed and motor torque have some fluctuation in the sunroof running process, mainly owing to the internal and external disturbances of sunroof system. Fig. 6(c) reflects the pinch detection of torque rate with true calculation, Kalman filter and the proposed method. From the result in Fig. 6(c), the influence of disturbances on the recognition of the pinch state can be weakened with

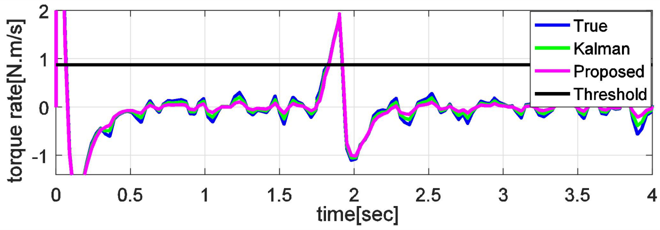
Kalman filter and with the proposed method, but it is obvious that the pinch detection with the grey estimation and compensation has better performances.



(a)



(b)

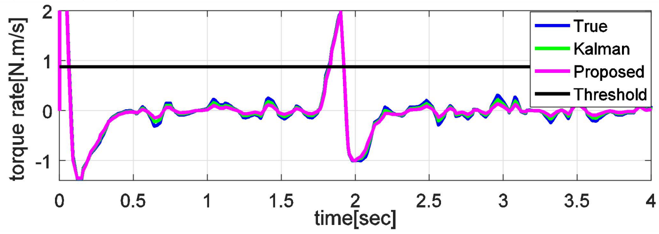


(c)

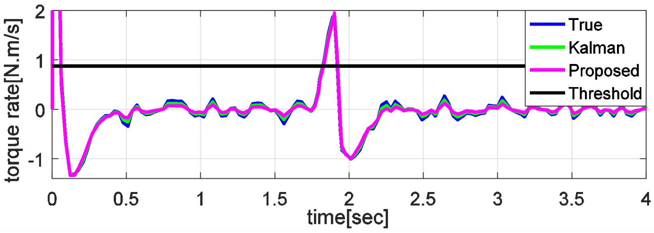
Figure 6. Pinch detection under normal conditions. (a) Angular velocity. (b) Estimated torque. (c) Estimated torque rate.

Pinch Detection under Abnormal Conditions

The normal value of the sunroof motor input voltage U is 12V, and the normal values of motor parameters are shown in Table. 1, but it may vary due to the electrical aging, complex road conditions and residual electricity. In order to test the abnormal conditions of different input voltage and parameter perturbation, we change the input voltage with 9V and 15V, and change the torque constant K_t with $0.9K_t$ to test the pinch detection performance with the method proposed in this paper and with Kalman Filter. The test results with the input voltage with 9V and 15V are shown in Fig. 7 (a) and Fig. 7(b). From Fig.7, we know that the pinch detection is still good and even better than the Kalman Filter. The test result with $0.9K_t$ is shown in Fig. 8. From Fig. 8, we find that the proposed pinch detection method is nearly not affected by the torque constant perturbation. From the test in the abnormal condition, it can indicate that the proposed pinch detection method has a better robust performance.



(a)



(b)

Figure 7. Pinch detection under abnormal conditions of different supply voltages. (a) Estimated torque rate under 9V. (b) Estimated torque rate under 15V.

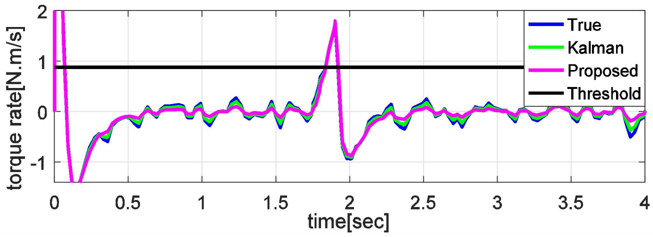
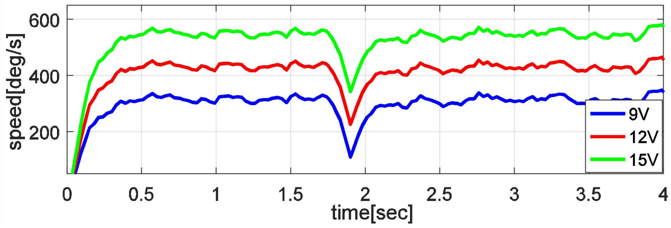


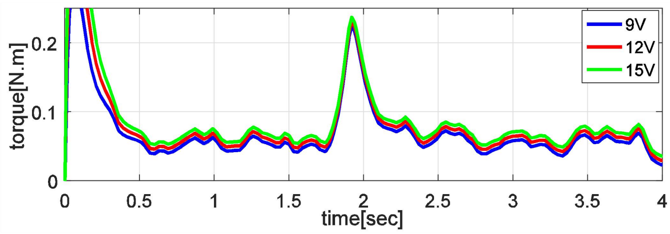
Fig. 8. Pinch detection under the abnormal condition of $0.9k_t$.

Sensitivity Test under Different Supply Voltages

In order verify the result that the pinch detection by torque rate is better than the motor speed and torque in different conditions, the curves of the motor speed, the pinch detection torque and the pinch detection torque rate are analyzed in different input voltages. In general, the range of motor input voltage is 9~16[V] in engineering [16]. Since U changes slowly in most cases, it can be regarded as a constant within a short period. In order to test the pinch detection algorithm in this paper, three cases of the supply voltages 9V, 12V and 15V are selected. The test results are shown in Fig. 9.



(a)



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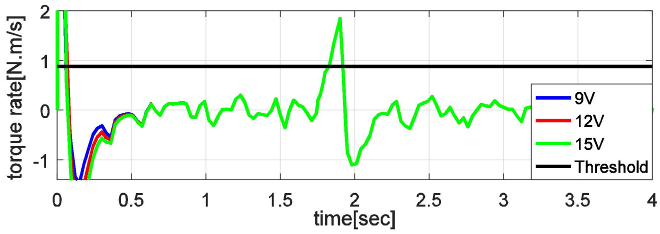


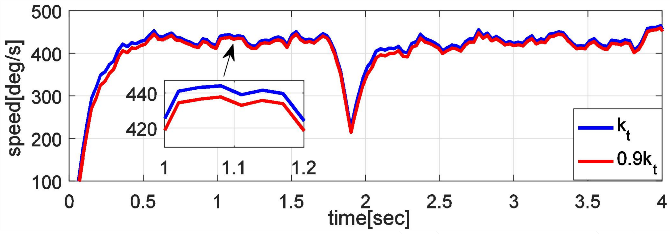
(c)

Figure 9. Pinch detection results for U=9V, 12V, 15V. (a) Angular velocity. (b) Estimated torque. (c) Estimated torque rate

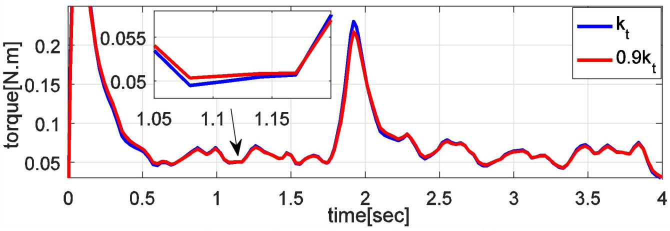
As shown in Fig. 9, the motor rotational speed has a big fluctuation with the change of supply voltages, the pinch detection torque has a small fluctuation with the change of input voltages, and the pinch detection torque rate almost has no fluctuation with the change of input voltages. From the results in Fig. 8 we know that the motor rotational speed and the pinch detection torque are not suitably selected to detect the pinch state. However, the proposed torque rate detection method has good performances in detecting the electric sunroof pinch state.

Sensitivity Test under Parametric Uncertainty

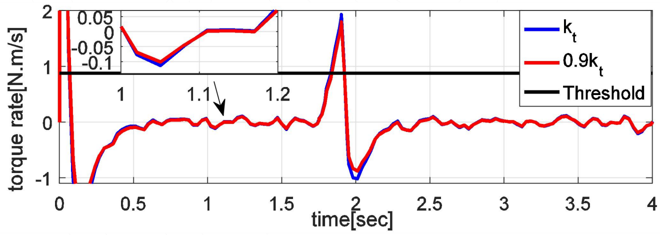
In the realistic electric sunroof system, the parameters of DC motor will perturb with the wear of mechanical mechanism. In this condition, the normal value of motor rotational speed, torque and torque rate may change. In order to verify the result that the pinch detection rate method is better than the motor speed and the pinch detection torque, we conduct the test by changing the normal torque constant K_t with 0.9 K_t and observing the motor rotational speed, torque and torque rate. The test results are shown in Fig.10.



(a)



(b)



(c)

Figure 10. Estimation results in parametric uncertain case ($\overline{K}_t - 0.9K_t$). (a) Angular velocity. (b) Estimated torque. (c) Estimated torque rate.

As can be seen from Fig.10, we know that the motor rotational speed and pinch detection torque all have a little fluctuation with parameter perturbation, but the proposed method with pinch detection torque rate still guarantees reliable pinch detection performance.

4. Conclusion

In this paper, a new practical and robust pinch detection algorithm based on grey theory has been proposed for the car sunroof anti-pinch control system. This smart pinch detection algorithm is based on the grey estimation and grey compensation for the uncertain disturbances, so as to eliminate the influence of the internal parameters perturbation and external disturbance. This paper makes the following contributions. Firstly, it selects the pinch detection torque rate as a criterion of pinch detection, and the tests show that the torque rate method is reliable and robust in the pinch detection even in the presence of parametric uncertainty of a motor. Secondly, to detect the pinch condition, the threshold of torque rate has been derived by referring to the existing safety regulation and repeated test. From the experiments in the laboratory, it has been confirmed that the proposed algorithm shows robust and reliable pinch detection performance in a smart way. As a result, it will be a practical option for the design of car sunroof safety devices.

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