A study on Clamping force Estimation of EMB for Fuel-cell vehicle using Sliding mode observer

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Abstract
A design and verification of sliding mode observer for estimation and control of clamp-force of Electro-Mechanical Brake (EMB) were described in this paper. Researches for elimination of a clamp-force sensor from brake-by-wire system are progressed due to implementation difficulties and cost issues. In the conventional studies, clamp-force is estimated from characteristic curve based on a contact point between brake pads and brake disk. In existing method, detection of accurate contact point is required. Otherwise, it causes the reduction of control performance and incorrect operation of EMB. With the sliding mode observer, it is possible to estimate the contact point and control clamp-force of EMB with considering of ageing of EMB system such as the abrasion of brake pad. The relationship between clamping force and position of brake pad is made up to lookup table, and clamping force control algorithm is designed using the lookup table. The designed Sliding mode observer and clamping force estimation and control algorithm are validated by experiments on the test bench.

Keywords: EMB, Electro-mechanical brake, Sliding mode Observer, Clamping force estimation, Fuel-cell

1 Introduction
Recently one of the primary issues of vehicle electronic-control system development is applied in the x-by-wire system using communication technologies and electric motor technology. a Brake-by-wire system, Replace the hydraulic link to the brake pedal from the brake actuator used in the existing hydraulic brake system to an electrical wire, and the brake actuator is used as an electric motor electro-mechanical brake (EMB) [1-2].
Besides, EMB has been developed as enhanced brake system by cooperation control with regenerative braking system of fuel-cell vehicle.
It is necessary to control EMB with feedback of clamping force information for precise control of clamping force. By use of force sensors to measure clamping force in EMB or electric parking brake (EPB) systems is simple solution. However, it is difficult to install the force sensor because of the limited mounting space and the increase of cost. Therefore, clamping force estimation methods without using the force sensor were proposed for EMB systems.
In [3], clamping force estimation method from the characteristic curve between the position of brake pad and the clamping force is proposed. On the other hand, clamping force estimation method by analysing the relationship between motor rotation
angles and clamping force in frequency domain in [4].
And in [5], clamping force estimation algorithm, considering hysteresis caused of backlash, based on the relationship curves of between motor rotation angle and clamping force is proposed. In these previous studies, it is necessary to compensate the change of contact point of brake pad and disk caused of the EMB system ageing such as abrasion of brake pads.
To solve this problem, the contact point is estimated by using the relationship between variation of motor torque and position of brake pad in [6]. And in [7], contact point estimation method using motor angular velocity is proposed. In this paper, clamping force estimation and control algorithm based on the relationship of position of brake pad and clamping force is proposed. The relationship of brake pad position and clamping force is defined by sliding mode observer.

2 System Modeling
The EMB system includes a caliper, brake pad and permanent magnet synchronous motor (PMSM). A caliper and PMSM are connected via gear set and ball screw. The PMSM generates electrical torque, and generated electrical torque converts to clamping force by ball screw, brake pad and disk.
Between brake pad and disk, there is a gap. The brake pad does not contact to the disk, which means no clamping force generates in this section. The contact point of brake pad and disk describes as \( x_{F_0} \) in Figure 2. Beyond contact point, clamping force is generated according to position of brake pad as shown in Figure 2 [3].

The electrical torque \( T_M \) is represented as shown in equation (1) and (2) using gear ratio and efficiency \( N \), inertia \( J \) and friction \( B \). Clamping
force $F_{cl}$ is related with electrical torque of motor as Figure 3.

$$T_m = J\ddot{\omega} + B\dot{\omega} + F_{cl} \cdot N \quad (1)$$

$$T_m = T_f + T_{bi} + T_L \quad (2)$$

Parameters using in this paper are shown in Table 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J$</td>
<td>4.58e-6 kgm$^2$</td>
</tr>
<tr>
<td>$B$</td>
<td>1.19e-5 Nm/rad/s</td>
</tr>
<tr>
<td>$N$</td>
<td>1/2400</td>
</tr>
<tr>
<td>$P$</td>
<td>4EA</td>
</tr>
<tr>
<td>$\lambda_m$</td>
<td>6.34mWb</td>
</tr>
<tr>
<td>$R_u$</td>
<td>77m$\Omega$</td>
</tr>
<tr>
<td>$L_d$</td>
<td>100 $\mu$H</td>
</tr>
<tr>
<td>$L_q$</td>
<td>145 $\mu$H</td>
</tr>
</tbody>
</table>

### 3 Sliding mode Observer Design

In this chapter, the proposed sliding mode observer design, which estimates clamping force of EMB, is described. Equation (3) is obtained from equation (1) and observer for motor angular velocity is described in equation (4) which is obtained from equation (3). A constraint of a constant observer gain in equation (4) is $l > 0$.

The dynamic of the mismatch $\omega$ can be obtained using equation (5) and observer for motor angular velocity is obtained in equation (6) using dynamic of the mismatch $\omega$ [8-9].

$$J\ddot{\omega} = T_m - B\dot{\omega} - F_{cl} \cdot N \quad (3)$$

$$J\ddot{\omega} = T_m - B\dot{\omega} - l \cdot \text{sign}(\omega) \quad (4)$$

$$\ddot{\omega} = \omega - \dot{\omega} \quad (5)$$

$$J\ddot{\omega} = -B\omega + F_{cl} \cdot N - l \cdot \text{sign}(\omega) \quad (6)$$

The sliding mode reach condition is described by equation (7) [8]. The sliding mode observer gain $l$, to enforce the sliding mode ($s = \omega = 0$), is determined by applying the condition of equation (7). The “$s$” represents the sliding manifold that describes the sliding condition in all equations [10].

$$\ddot{\omega} \cdot \dot{\omega} < 0 \quad (7)$$

Therefore the sliding mode observer gain $l$ is represented as equation (8) and (9).

$$\left( F_{cl} \cdot N - B\omega \right) \cdot \dot{\omega} < l \cdot \text{sign}(\omega) \cdot \dot{\omega} \quad (8)$$

$$\therefore l > \frac{F_{cl} \cdot N - B\omega}{\text{sign}(\omega)} \quad (9)$$

And sliding mode observer gain $l$ is represented as equation (10) and (11) considering of dynamic of the mismatch $\omega$.

$$l > F_{cl} \cdot N - B\omega, \text{ (if } \dot{\omega} > 0) \quad (10)$$

$$l > -(F_{cl} \cdot N - B\omega), \text{ (if } \dot{\omega} < 0) \quad (11)$$

The sliding mode observer gain $l$ is determined as equation (12) and (13).

$$\therefore l > \left| F_{cl} \cdot N - B\omega \right| \quad (12)$$

$$l > 4.21 \quad (13)$$

High sliding-mode observer gain helps enforce the sliding mode, and suppress influence of disturbances and uncertainties in system behavior. On the other hand, it causes oscillation in estimation result usually referred to as chattering of sliding mode observer [11].

Equations (14) to (16) are obtained using the concept of equivalent control [12].

After the reaching phase of the sliding mode, the dynamic of the mismatch $\omega$ is equal to zero. Therefore, the clamping force of EMB can be obtained as below in Eq. (16).

$$J\ddot{\omega} = -B\omega + F_{cl} \cdot N - (l \cdot \text{sign}(\omega))_{eq} \quad (14)$$

$$F_{cl} \cdot N - (l \cdot \text{sign}(\omega))_{eq} = 0 \quad (15)$$

$$F_{cl} = \frac{(l \cdot \text{sign}(\omega))_{eq}}{N} \quad (16)$$

To determine the equivalent control $(l \cdot \text{sign}(\omega))_{eq}$, a second-order Butterworth filter is employed. The cut-off frequency of the Butterworth filter is set to 1.5Hz according to the minimum time of clamping force rise to the max value.
To estimate the clamping force of EMB, electric torque of motor has to be determined. The electric torque of motor $T_m$ is determined by equation (17) which is the electric torque equation of IPMSM. Equations (17) and (18) are constant value for reaction torque and reluctance torque of IPMSM, respectively.

\[
T_m = K_{Tm} \cdot i_q + K_{Ti} \cdot i_d \cdot i_q
\]  
(17)

\[
K_{Tm} = \frac{P}{2} \cdot \frac{3}{2} \cdot \lambda_m
\]  
(18)

\[
K_{Ti} = \frac{P}{2} \cdot \frac{3}{2} \cdot (L_d - L_q)
\]  
(19)

### 4 Clamping Force Control

For estimation and control clamping force, characteristic curve of clamping force and brake pad position has to be determined. To determine the characteristic curve, clamping force estimation result of designed sliding mode observer is used.

At initialization state of EMB system, EMB ECU generates clamping force by moving brake pad through mechanical stop which is the position of maximum clamping force. And sliding mode observer estimated clamping force at the same time. The lookup table can be determined using estimated clamping force and position of brake pad as shown in Figure 5. In the lookup table, clamping force axis is divided in the same interval. The point of 0N clamping force is contact point, and clamping force is generated beyond the contact point.

Using the lookup table of clamping force and brake pad position, the clamping force controller is designed as Figure 5.

With measured physical values which are the position of brake pad $x$, angular velocity of electric motor $\omega$, and applied current of electric motor $i$, the feedback control is executed. The output voltage is obtained by the feedback control.

### 5 Experiments

In this chapter, a designed sliding mode observer and clamping force estimation and control algorithm are verified on the test bench. The block diagram of experiments environment is as shown Figure 7.

There is EMB ECU for Estimation clamping force and control EMB and it includes 3-phase inverter for drive PMSM.

Also, it includes signal conditioning circuit for measurement of physical values, and communication circuit to connect to PC for monitoring and generation of control reference.
For the verification, additional load cell and indicator for measurement of the clamping force is included in the experiments environment.

The lookup table based on the clamping force estimation result using sliding mode observer is as Figure 10. In Figure 10, the contact point is determined on the 0.97mm. In the region between 0 ~ 0.97mm, it is the gap of brake pad and disk, which means there is no clamping force in this region.

In Figure 9, it is comparison of clamping force estimated with sliding mode observer and clamping force measured with load cell. In the result of estimation of clamping force with sliding mode observer, there is difference from measured clamping force below 100N. It is the excluded region of lookup table as low generated torque of electric motor.

The clamping force aspect of estimation with sliding mode observer and measurement with load cell is similar, particularly between 100N to 700N which is primary operating region. The maximum simultaneous error is below 40N.

Figure 11 shows the relationship between clamping force measured using load cell and clamping force estimated using lookup table. The maximum simultaneous error is below 40N. This means that it is possible to use this lookup table for estimation and control clamping force instead force sensor such as load cell.

Figure 12 shows the result of proposed estimation and control algorithm of clamping force. Control references of clamping force are 200N, 400N and
700N, respectively. The maximum response time is 0.5sec, maximum steady state error is 20N.

Figure 12: Clamping force control result

6 Conclusion

Recently, clamping force estimation methods without using the force sensor were proposed in many researches. However it is necessary to compensate the change of contact point of brake pad and disk caused of the EMB system ageing such as abrasion of brake pads in previous researches. In this paper, clamping force estimation and control algorithm based on the relationship of position of brake pad and clamping force with sliding mode observer is proposed. Designed sliding mode observer is verified by experiment on the test bench. By using designed sliding mode observer, it can be possible to estimate the clamping force. The clamping force and contact point can be estimated with considering of ageing of EMB system such as the abrasion of brake pad.

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References

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