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RESISTANCE ESTIMATION OF A PWM-DRIVEN SOLENOID

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ABSTRACT–This paper proposes a method that can be used for the resistance estimation of a PWM (Pulse Width Modulation)-driven solenoid. By using estimated solenoid resistance, the PWM duty ratio was compensated to be proportional to the solenoid current. The proposed method was developed for use with EHB (Electro-Hydraulic Braking) systems, which are essential features of the regenerative braking system of many electric vehicles. Because the HU (Hydraulic Unit) of most EHB systems performs not only ABS/TCS/ESP (Electronic Stability Program) functions but also service braking function, the possible duration of continuous solenoid driving is so long that the generated heat can drastically change the level of solenoid resistance. The current model of the PWM-driven solenoid is further developed in this paper; from this a new resistance equation is derived. This resistance equation is solved by using an iterative method known as the FPT (fixed point theorem). Furthermore, by taking the average of the resistance estimates, it was possible to successfully eliminate the effect of measurement noise factors. Simulation results showed that the proposed method contained a sufficient pass-band in the frequency response. Experimental results also showed that adaptive solenoid driving which incorporates resistance estimations is able to maintain a linear relationship between the PWM duty ratio and the solenoid current in spite of a wide variety of ambient temperatures and continuous driving.

KEY WORDS : Estimation algorithm, Electrical driving, Electro-hydraulic system, Automotive braking control

1. INTRODUCTION

The EHB (Electro-Hydraulic Braking) system is a wet-type BBW (Brake By Wire) system and is expected to make up the next generation of braking systems (Reuter *et al.*, 2003; Petruccelli *et al.*, 2003). EHB systems are generally composed of a BPU (Brake Pedal Unit), a HU and an ECU (Electronic Control Unit). Figure 1(a) depicts the hydraulic circuit as found in EHB systems. During normal operations, an isolation valve disconnects the hydraulic circuit between the BPU and the HU and the HU controls wheel pressures according to the driver's intentions. The BPU absorbs brake oil obtained by brake pedal operations and makes drivers feel like they are using a conventional braking system. When there are system failures or situations when the systems are turned off, the hydraulic circuit between the BPU and the HU can provide a mechanical backup line to ensure emergency braking. Although EHB systems cannot completely eliminate hydraulic components, they can separate wheels from brake pedals and provide perfect active braking (Reuter *et al.*, 2003). Active braking, which can be defined as a braking operation that does not require pedal operations by drivers, is an important requirement of new system functions such as ACC (Adaptive Cruise Control), CA (Collision Avoidance) and autonomous vehicles. Additionally, because the regenerative braking systems of EV (Electric Vehicles)/HEV (Hybrid Electric Vehicles) require complete separation between brake pedals and wheels, EHB are thought to provide a unique practical solution.

Almost every HEV has already adopted an EHB system to implement regenerative braking, an essential way of achieving high fuel efficiency (Sakai, 2005; Nakamura *et al.*, 2002; Gao and Ehsani, 2002). Consequently, the growth of the HEV market means an increase in the popularity of EHB systems. The Prius, which was launched successfully in the Japanese market as the first mass-produced hybrid vehicle in 1997, also adopted an EHB system (Sakai, 2005). The Prius was an immediate success and more than 127,000 units were sold in six years (Yaegashi, 2005).

EHB systems generally require a robust method for solenoid current control. In general, EHB HU systems use poppet-type valves actuated by solenoids, and the solenoid current is controlled by a PWM-driving method. Figure 1(c) shows a typical model of PWM driving. The poppet-type valve actuated by a PWM-driven solenoid can reduce the price of the actuator and the total system

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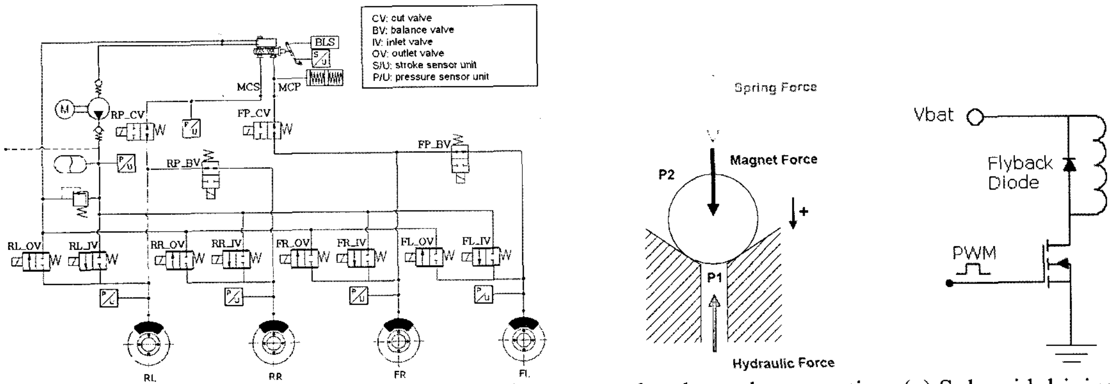


(a) Hydraulic circuit of an EHB system (b) Forces related to valve operation (c) Solenoid driving circuit

Figure 1. EHB system valve conrol.

(Verseveld and Bone, 1997).

Some forces related to the poppet-type valve include spring forces, hydraulic forces and magnetic forces, as shown in Figure 1(b). By controlling the solenoid current, the ECU can control the magnetic force and net force imposed on the valve. Because the solenoid resistance changes over a wide range, e.g. ~70% ~ 100%, the relationship between the PWM duty ratio and the solenoid current varies as solenoid resistance changes. Therefore, an estimation of solenoid resistance is inevitable for successful solenoid current control and pressure control to compensate for the PWM duty ratio. Because EHB HU systems implement a CBS (Conventional Braking System) function, the duration of continuous solenoid driving can be extended drastically and the compensation method used by the ESP (Electronic Stability Program) cannot be applied to the EHB system. In terms of regenerative braking, the duration of continuous driving becomes longer and the actuation strength becomes stronger because the necessary wheel pressures have to change continuously, even if the driver maintains their brake pedal position (Nakamura *et al.*, 2002).

This paper introduces a model for the average solenoid current driven by the PWM method. If the frequency of the PWM signal is sufficiently high with respect to the time constant of the solenoid, the average current of the solenoid can be modeled as if the solenoid was driven by a DC voltage source proportional to the PWM duty ratio. With this simple model, an equation can be derived that explains the solenoid current with the given initial current, the voltage of the power source and the PWM duty ratio. Because the solenoid current is measured with an embedded circuit, the solenoid current equation refers to solenoid resistance. Unfortunately this equation cannot be solved directly.

By using an iterative method, i.e. a FPT (Fixed Point Theorem), the solenoid resistance equation can be solved economically. Because the equation is simple and can be calculated in terms of integer operations, the consumption of computational power is limited to a very small amount. Taking the average of the calculated solenoid resistances over a fixed duration eliminates the effect of modeling errors and measurement noise because averaging can generally eliminate Gaussian noise. With the estimated solenoid resistance, the PWM duty ratio can be compensated to make the relationship between the PWM duty ratio and the solenoid current linear and static.

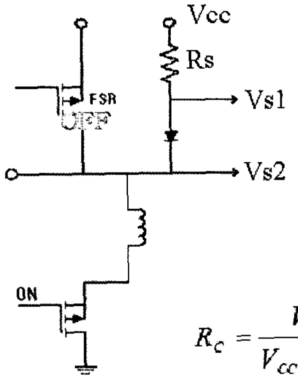
The period of the current control of the EHB system is short with respect to changes in solenoid resistance. Therefore, an adaptive control method that incorporates the estimation of slow varying parameters, i.e. solenoid resistance, is more efficient and effective than direct control of a fast varying current. With simple integer calculations and averaging, the proposed method economically achieves a robust current controller. Simulation refers to the frequency response of the proposed method which shows that the proposed method has a pass-band wide enough to immediately follow changing solenoid resistances even in the worst situations. Experimental results confirmed that the suggested method is very robust to changes of solenoid resistance and measurement noise factors.

2. NEW REQUIREMENTS

EHB systems must be able to estimate solenoid resistance while driving solenoids because the duration of continuous driving can be long and the solenoid resistance variations caused by generated heat are too large to be ignored.

2.1. Previous Method Used by the ESP

Although the ESP uses the same solenoid driving mechanism, it can ignore the variations of solenoid resistance because the duration of solenoid driving is short. Before the ESP starts to drive the solenoid, the ESP estimates the solenoid resistance and assumes that this resistance *will*



$$R_C = \frac{V_{S2}}{V_{CC} - V_{S1}} \times R_S$$

Figure 2. The ESP method.

remain constant during solenoid driving. Figure 2 shows the circuit and formula used in the ESP method. Before the start of solenoid driving, the ESP turns off the power source switch (FSR). When the ESP turns on the solenoid driving FET (Field Effect Transistor), current flows from the regulated DC power V_{CC} to the ground. The ESP measures two voltages, i.e. V_{S1} and V_{S2}, in order to estimate the forward voltage of the diode. The flowing current can be calculated with the V_{CC}-V_{S1} and the R_S. With the current and the V_{S2}, the solenoid resistance R_C can be calculated (Choi *et al.*, 2003). However, because this method can be used only when the power source switch is turned off, this method cannot be applied to EHB systems.

2.2. Some Problems of Alternative Solutions

The first solution is a table-based method; this is the usual procedure in automotive control to compensate for parameter variance. However, constructing a table for the estimation of solenoid resistance requires three indexes: the current difference, the power source voltage, and the PWM duty ratio. A table like this would be too large to be embedded into a practical ECU.

A software-based current feedback controller is the second solution. However, because this method requires a shorter control period and a larger amount of computational power, it seems to go beyond the scope of a 16-bit micro-controller.

A current feedback circuit is the third solution because this kind of circuit is widely used in solenoid current control systems. However, this method requires a DAC (Digital to Analog Conversion) ports: these are not commonly used in automotive ECU systems to establish target currents. Furthermore, current feedback circuits which compare target currents with measured currents then turn the driving FET systems on or off are supposed to generate random driving signals at a low frequency range; these signals can cause EMC (Electro-Magnetic Compatibility) problems. PI controller circuits which use error terms to adjust PWM duty ratios need complicated hardware circuits. Also, the frequency characteristics of target currents have to be limited to low frequency ranges because of heavy low-pass filters used for current measurement.

2.3. New Requirements

The new requirements of solenoid resistance estimation for EHB systems can be summarized as follows:

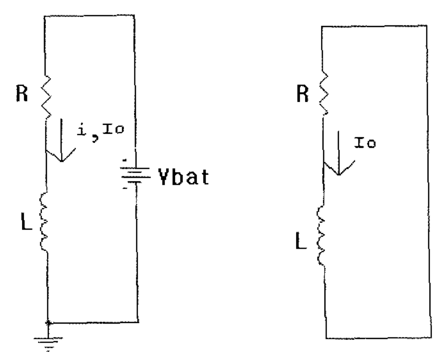
- New methods must be able to estimate solenoid resistance while driving solenoids.
- New methods must be able to cope with noise factors in the measurement of solenoid currents.
- Additional computational loads must be small.
- Additional memory consumption needs must be small.

3. MODEL FOR AN AVERAGE SOLENOID CURRENT

In this section, a model for an average solenoid current is derived. Because a solenoid shows inductance properties as well as resistance properties, a solenoid current can be modeled by first order dynamics.

3.1. Differential Equation of the Solenoid Current

Figure 3 shows a solenoid driving circuit. The solenoid is replaced with a series connection of the resistance property R and the inductance property L. The FET is modeled as an ideal switch driven by a PWM signal and the diode is modeled as a unidirectional switch. During the PWM-ON state, the solenoid is driven by a DC voltage source V_{BAT} as shown in Figure 3(a); Equation (1) is set up by using the KVL (Kirchhoff Voltage Law) (Vaughan and Gamble, 1996). Here, $i(t)$ denotes the solenoid current and τ is the time constant of the solenoid. Equation (2) is the solution of Equation (1) and I_S refers to a saturated current. The solenoid current exponentially increased from the initial current I_O to the saturated current I_S.



(a) ON state (b) OFF state

Figure 3. Equivalent circuits for the PWM-ON/OFF states.

$$Ri+L\frac{di}{dt}=V_{BAT} \tag{1}$$

$$\begin{aligned} i(t)&=Is-Ise^{-\frac{t}{\tau}}+Io\cdot e^{-\frac{t}{\tau}} \\ &=Io+(Is-Io)\left(1-e^{-\frac{t}{\tau}}\right) \end{aligned} \tag{2}$$

where, $Is=\frac{V_{BAT}}{R}$, $\tau=\frac{L}{R}$

During the PWM-OFF state, the freewheeling diode, or the flyback diode, was turned on and it made a loop without a voltage source, as shown in Figure 3(b). Ignoring the forward voltage drop of the freewheeling diode, Equation (3) was set up by the KVL. Equation (4) is the solution of Equation (3). The solenoid current decreased exponentially from the initial current I_O to zero.

$$Ri+L\frac{di}{dt}=0 \tag{3}$$

$$i(t)=Io\cdot e^{-\frac{t}{\tau}} \tag{4}$$

3.2. Sequence of the Initial Current

Generally, when PWM signal drives the solenoid FET, the PWM-ON state and the PWM-OFF state are repeated in turn. The final solenoid current of the previous state becomes the initial current of the ongoing state. Equations (2) and (4) are generalized as a summation of the geometric series.

$I_{O+}(n)$ denotes the initial current of the n[th] PWM-ON state and $I_{O-}(n)$ denotes the initial current of the n[th] PWM-OFF state as depicted in Figure 4. δ denotes the PWM duty ratio and has a value from 0 to 1. T is the period of the PWM driving signal. The initial current was calculated recursively from the first period, as shown below:

$$I_{0+}(1)=0$$

$$I_{0-}(1)=Is-Ise^{-\frac{\delta T}{\tau}}$$

$$I_{0+}(2)=Ise^{-\frac{(1-\delta)T}{\tau}}-Ise^{-\frac{T}{\tau}}$$

$$I_{0-}(2)=Is-Ise^{-\frac{\delta T}{\tau}}+Ise^{-\frac{T}{\tau}}-Ise^{-\frac{T+\delta T}{\tau}}$$

$$I_{0+}(3)=Ise^{-\frac{(1-\delta)T}{\tau}}-Ise^{-\frac{T}{\tau}}+Ise^{-\frac{(1-\delta)T+T}{\tau}}-Ise^{-\frac{2T}{\tau}}$$

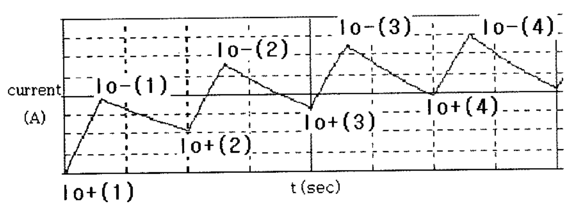


Figure 4. Sequence of the initial current.

$$I_{0-}(3)=Is-Ise^{-\frac{\delta T}{\tau}}+Ise^{-\frac{T}{\tau}}-Ise^{-\frac{T+\delta T}{\tau}}+Ise^{\frac{2T}{\tau}}-Ise^{-\frac{2T+\delta T}{\tau}}$$

$$\begin{aligned} I_{0+}(4)=&Ise^{-\frac{(1-\delta)T}{\tau}}-Ise^{-\frac{T}{\tau}}+Ise^{-\frac{T+(1-\delta)T}{\tau}}-Ise^{-\frac{2T}{\tau}} \\ &+Ise^{-\frac{2T+(1-\delta)T}{\tau}}-Ise^{-\frac{3T}{\tau}} \end{aligned}$$

Careful observation shows that the n[th] initial current is the summation of the geometric series. Equation (5) defines the initial current of the n[th] PWM-ON state and Equation (6) defines the initial current of the n[th] PWM-OFF state.

$$I_{0+}(n)=Is\left(e^{-\frac{(1-\delta)T}{\tau}}-e^{-\frac{T}{\tau}}\right)\frac{1-e^{-\frac{(n-1)T}{\tau}}}{1-e^{-\frac{T}{\tau}}} \tag{5}$$

$$I_{0-}(n)=Is\left(1-e^{-\frac{\delta T}{\tau}}\right)\frac{1-e^{-\frac{nT}{\tau}}}{1-e^{-\frac{T}{\tau}}} \tag{6}$$

3.3. Average Solenoid Current

The integration of the solenoid current during the n[th] PWM-ON state was calculated by integrating Equation (1) and Equation (5) from 0 to δT.

$$I_{ON}=\int_0^{\delta T}\left\{\begin{aligned} &\frac{V_{BAT}}{R}-\frac{V_{BAT}}{R}e^{-\frac{t}{\tau}} \\ &+\frac{V_{BAT}}{R}\left(e^{-\frac{(1-\delta)T}{\tau}}-e^{-\frac{T}{\tau}}\right)\frac{1-e^{-\frac{(n-1)T}{\tau}}}{1-e^{-\frac{T}{\tau}}}e^{-\frac{t}{\tau}} \end{aligned}\right\}dt$$

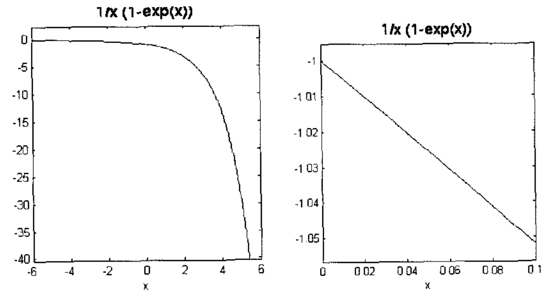
Similarly, the integration of the solenoid current during the n[th] PWM-OFF state was calculated by integrating Equation (4) and Equation (6) from 0 to $(1-\delta)T$.

$$I_{OFF}=\int_0^{(1-\delta)T}\left\{\frac{V_{BAT}}{R}\left(1-e^{-\frac{\delta T}{\tau}}\right)\frac{1-e^{-\frac{nT}{\tau}}}{1-e^{-\frac{T}{\tau}}}e^{-\frac{t}{\tau}}\right\}dt$$

By dividing the summation of I_{ON} and I_{OFF} by the PWM period T, the equation of the average solenoid current at time index n was derived as in Equation (7). By replacing the discrete index nT with the continuous time t, the equation of the average solenoid current at time t was derived as in Equation (8). If the initial current of the first state was not zero, a term reflecting the initial current which decreased exponentially, had to be added.

$$i(n)=\frac{V_{BAT}}{R}\delta\left\{1+\frac{\tau}{\delta T}\left(1-e^{\frac{\delta T}{\tau}}\right)e^{-\frac{nT}{\tau}}\right\} \tag{7}$$

$$i(t)=\frac{V_{BAT}}{R}\delta\left\{1+\frac{\tau}{\delta T}\left(1-e^{\frac{\delta T}{\tau}}\right)e^{-\frac{t}{\tau}}\right\} \tag{8}$$



(a) -6<x<6 (b) 0<x<0.1

Figure 5. Coefficient function.

3.4. Approximation of the Average Solenoid Current

By applying realistic values to the parameters, Equation (8) was approximated in a very simple form. The coefficient of the exponential term of Equation (8) is a function of the time constant τ, the PWM period T and the duty ratio δ. The introduction of a new variable x made the coefficient become a function of x as shown below:

$$x=\frac{\delta T}{\tau},\ \frac{\tau}{\delta T}\left(1-e^{\frac{\delta T}{\tau}}\right)\Rightarrow\frac{1}{x}(1-e^{x})$$

Figure 5(a) shows a graph of the coefficient function when x ranged from –6 to 6. If the range of x was 0~0.1, the coefficient function had a value of –1, as shown in Figure 5(b). Consequently, if the PWM period T was sufficiently smaller than the solenoid time constant τ, x had a very small value and the coefficient function was approximated to the constant –1. In our case, the solenoid time constant was 0.003 and the PWM frequency is 20 kHz (T=0.00005). Therefore, $x < 0.017$ and coefficients were treated as –1. By replacing the coefficient in Equation (8) with the approximation value –1, the approximated equation of average solenoid current was derived as shown in Equation (9). This equation shows that the average solenoid current had the same time constant as the instant solenoid current. Furthermore, it shows that the solenoid current exponentially changed and converged to a saturated current which was proportional to the PWM duty ratio. If the initial current of the first state was not zero, Equation (9) was modified as shown in Equation (10). Hereafter, Equation (10) is used to estimate the solenoid resistance.

$$i(t)=\frac{V_{BAT}\cdot\delta}{R}\left\{1-e^{-\frac{t}{\tau}}\right\} \tag{9}$$

$$\begin{aligned} i(t)&=\frac{V_{BAT}\cdot\delta}{R}+\left(Io-\frac{V_{BAT}\cdot\delta}{R}\right)e^{-\frac{t}{\tau}} \\ &=Io+\left(\frac{V_{BAT}\cdot\delta}{R}-Io\right)\left(1-e^{-\frac{t}{\tau}}\right) \end{aligned} \tag{10}$$

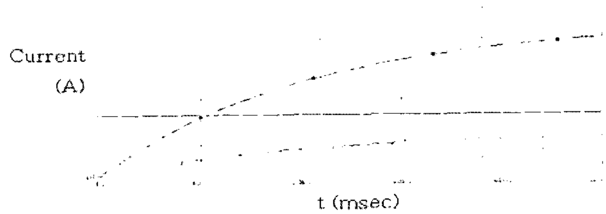


Figure 6. Behavior of an average solenoid current.

In Figure 6, the upper graph corresponds to the solenoid current that was driven by a DC voltage source. The lower graph shows the solenoid current driven by a PWM signal with a 30% duty ratio. Although the lower graph exponentially increased and decreased according to the PWM-ON or OFF states, the envelope of the lower graph was the same as that of the upper graph. This shows that the lower graph converged to a saturated current proportional to the PWM duty ratio.

4. ESTIMATION OF SOLENOID RESISTANCE

Because the equation of solenoid resistance cannot be solved in a closed form, an FPT (Fixed Point Theorem)-based iterative method was introduced (Burden, 2001). This section shows that this method proved robust with respect to temperature changes, measurement noise factors and modeling errors.

4.1. Approximation of Solenoid Resistance Equation

Solenoid currents measured at every control period T_C were defined as in Equation (11), which was acquired by replacing t in Equation (10) with T_C. I_O denoted the initial current of the ongoing control period. Solenoid resistance R satisfied the equation, which unfortunately could not be solved in a closed form.

$$i(Tc)=\frac{V_{BAT}\cdot\delta}{R}+\left(Io-\frac{V_{BAT}\cdot\delta}{R}\right)e^{-\frac{Tc}{\tau}} \tag{11}$$

Because an exponential function would have been unsuitable for implementation in an embedded environment, it was approximated with a polynomial expression. Also, because the resistance of the solenoid used in the EHB system ranged between 4~8 Ω, the Taylor series (centered at R=6) was selected. The first order polynomial expression yields many errors. The second order polynomial expression successfully approximated the exponential term. This expression is depicted in Figure 7 (T_C=1 msec, L=15 mH). Nevertheless, because Equation (12) was the third order polynomial expression in terms of R and replaced the exponential term with the second order Taylor series, it could not be solved in a closed form, either. The resistance R term contained in the time constant τ was explicitly expressed.

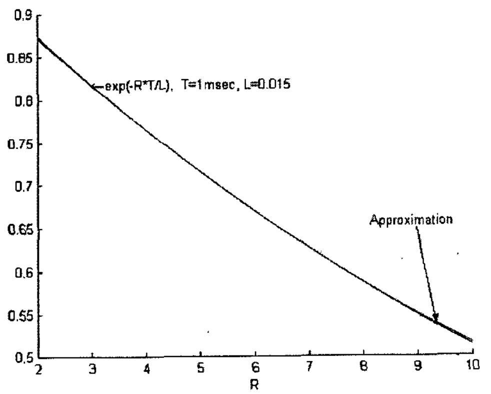


Figure 7. Taylor approximation of the exponential term.

$$i(Tc)=\frac{V_{BAT}\cdot\delta}{R}+\left(Io-\frac{V_{BAT}\cdot\delta}{R}\right) \tag{12}$$

4.2. The Iterative Method

In general, the iterative method requires a large computational load. However, because in this case the iteration period was the same as that of the control period T_C, the required computational load was smaller.

$$R=\frac{V_{BAT}\cdot\delta}{i(Tc)}+\left(\frac{Io\cdot R}{i(Tc)}-\frac{V_{BAT}\cdot\delta}{i(Tc)}\right) \tag{13}$$

$$\times(0.0014916\ R^2-0.0627\ R+0.99264)$$

$$R[n]=\frac{V_{BAT}[n]\cdot\delta[n]}{i[n]}+\left(\frac{i[n-1]\cdot R[n-1]}{i[n]}-\frac{V_{BAT}[n]\cdot\delta[n]}{i[n]}\right) \tag{14}$$

$$\times(p_1\cdot R^2[n-1]-p_2\cdot R[n-1]+p_3)$$

where, p_1=0.0014916, p_2=–0.06267, p_3=0.99264

To apply the FPT, Equation (12) was transformed into an iterative equation form, Equation (13). Equation (14) characterized the corresponding difference equation, representing a clear time sequence of related variables. $\delta[n]$ denoted the PWM duty ratio of the nth control period and $V_{BAT}[n]$ denoted the measured voltage of the power source at the beginning of the nth control period. $i[n-1]$ represented the initial current of the ongoing control period and was measured at the beginning of the nth control period. $i[n]$ denoted the measured current at the end of the nth control period. Consequently, the nth resistance $R[n]$ was calculated with the n-1th resistance $R[n-1]$, the measured currents, the measured power source voltage, and the applied PWM duty ratio. Equation (14) was calculated only once per each control period. A fixed point refers to the cross point between the LHS (Left Hand Side) graph and the RHS (Right Hand Side) graph of Equation (13). As R was calculated repeatedly according to Equation (14), R approached a true value as depicted in Figure 8. In the simulation, the true value of solenoid resistance was 5.2 Ω; it was assumed that the initial current was 1.2 A and the PWM duty ratio was 0.7.

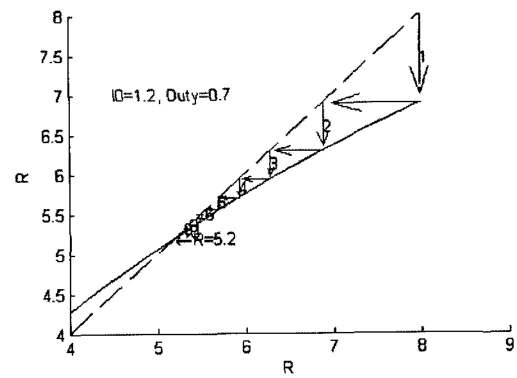


Figure 8. Calculated R approaching the fixed point.

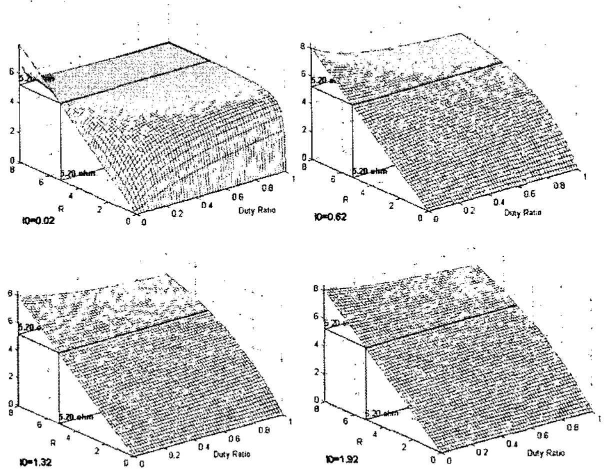
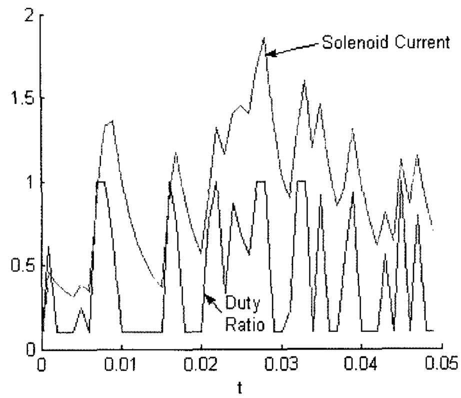


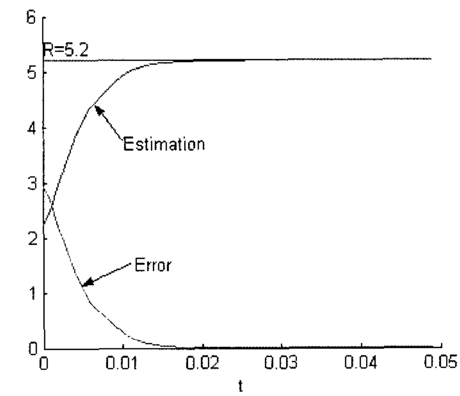
Figure 9. Fixed points of various initial currents and duty ratio.

In practical situations, a pressure controller generally sets the PWM duty ratio at every control period. According to the PWM duty ratio, the initial current and the final current varied. Furthermore, the voltage of the power source was not constant. In fact, the graphical shape of Equation (8) RHS changed at every control period. However, because the fixed point was the solution of the resistance equation, in any situation the point was fixed and ensured the convergence of solenoid resistance estimation. Figure 9 shows that in spite of various initial currents and PWM duty ratios, the fixed point was maintained.

Figure 10 is the result of simulation in which the PWM duty ratio represents a random number between 0.1 and 1. Figure 10 shows that the calculated solenoid resistance rapidly approached the true value. In practical situations, the ESP method can be used to estimate the initial value and the errors can be confined to a low level.



(a) Applied duty ratio and resultant current



(b) Resistance estimates and errors

Figure 10. Simulation results without noise factors.

4.3. Consideration of Noise Factors and Modeling Errors

Taking the sample mean of the calculated solenoid resistance made the proposed method robust with respect to measurement noise factors and modeling errors. Current measurements were supposed to produce additional noise factors. Additionally, modeling of the average solenoid current contained very few errors which were confined by a sufficiently high PWM frequency. In general, it is possible to assume that noise factors and modeling errors are WGN (White Gaussian Noise).

A graphical interpretation of Equation (11) reveals the effects of noise factors and modeling errors. The LHS graph of Equation (11) is a line parallel with the x-axis; the RHS graph of Equation (11) is a smoothly decreasing curve as depicted in Figure 11. Although it was impossible to calculate the resistance PDF (Probability Distribution Function) from the current measurement PDF, we assumed that the mapping from the current measurement PDF to the resistance PDF was approximately linear. Therefore, the resistance PDF was supposed to be WGN and the sample mean of the calculated solenoid resistance was supposed to be a good estimation of solenoid resistance.

Simulation results showed that if the WGN was added to the current measurement as shown in Figure 12(a), the calculated solenoid resistance also contained a WGN as shown in Figure 12(b). Even if the magnitude of the current noise factor was large (–50 mA~50 mA), the calculated solenoid resistance rapidly approached the true value and the sample mean was a good estimation of solenoid resistance, as shown in Figure 12(c).

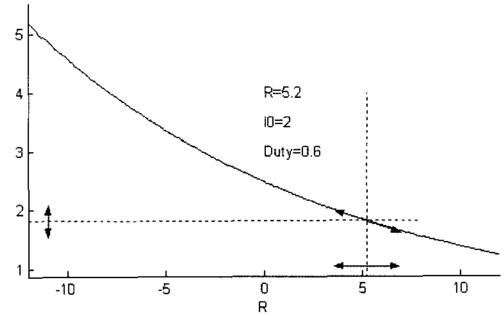
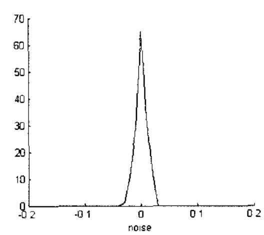
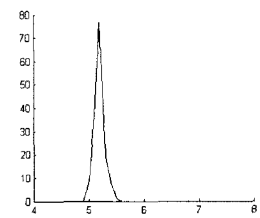


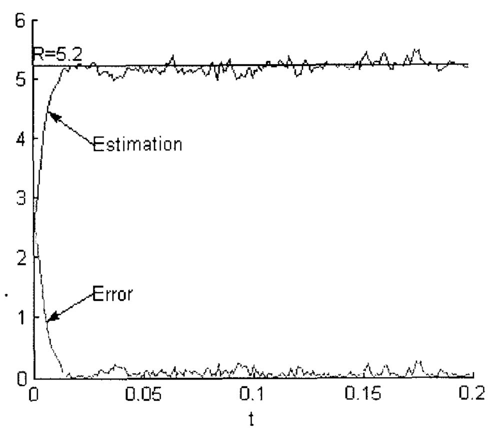
Figure 11. Relationship between the resistance PDF and the current PDF.



(a) Current noise PDF



(b) Resistance PDF

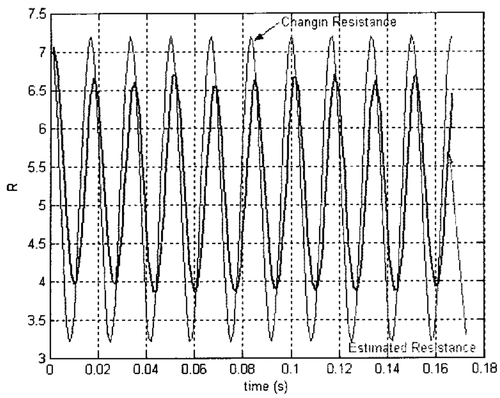


(c) Estimation results and errors

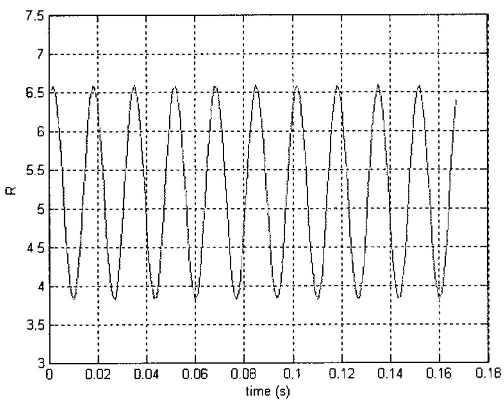
Figure 12. Simulation results with noise factors.

4.4. Frequency Response

The simulation results showed that the proposed method contained sufficient pass-band in the frequency responses. To verify whether the proposed method was able to immediately estimate the changing solenoid resistance, the frequency response of the proposed method was



(a) Changing resistance and estimated resistance



(b) Parameter estimation of estimated resistance

Figure 13. Experimental results for frequency response measurement.

measured by simulation. While changing the solenoid resistance in a sinusoidal waveform, the waveform of the estimation result was recorded. Such measurements were repeated while changing the sinusoidal frequency from 1 Hz to 500 Hz by 1 Hz steps, considering the control period as 1 msec. The sinusoidal offset was set to the resistance of normal temperature, i.e. 5.2 Ω, and the sinusoidal amplitude of input resistance was set to a sufficiently large value, i.e. 2 Ω, to cover the operational temperature range of our EHB system. Because the waveform of estimated solenoid resistance was supposed to have the same frequency as the input resistance sinusoid, the ML (Maximum Likelihood) estimation of the sinusoidal amplitude was able to measure the amplitude of the estimation results (Key, 1993). Figure 13(a) shows the waveform of estimated resistance when the input resistance was 60 Hz. Figure 13(b) shows the reconstructed sinusoid in which the parameter was estimated by the ML estimation.

With the sinusoidal amplitude of estimated resistance, the frequency response was constructed as shown in Figure 14. The acquired frequency response had the same

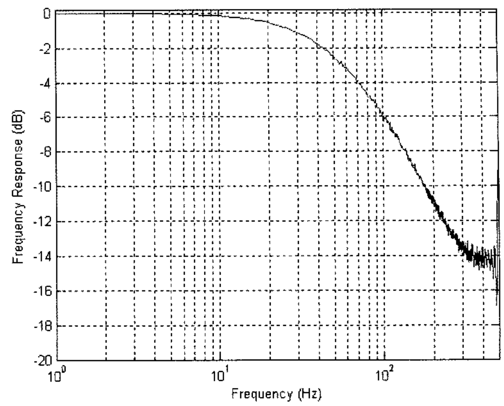


Figure 14. Frequency response of the proposed method.

characteristics as a typical low-pass filter. The cutoff frequency, or −3 dB point, was located at about 60 Hz. Therefore, the response of the proposed method would be sufficiently fast to cover the whole range of realistic situations.

5. COMPENSATION OF THE PWM DUTY RATIO

With the estimation of solenoid resistance, the PWM duty ratio was compensated to achieve a linear relationship between the PWM duty ratio and the solenoid current. The compensation method also used the measured voltage of the power source. The wheel pressure controller sent a PWM duty ratio to a hardware controller; the hardware controller then compensated for the PWM duty ratio by considering the variation of solenoid resistance and the power source voltage, as shown in Equation (15). Here, the reference voltage was 12 V and the reference resistance was the solenoid resistance of normal temperature.

$$\delta_{\text{modified}}[n]=\frac{\tilde{V}_{BAT}}{V_{BAT}[n]}\frac{\hat{R}[n]}{\tilde{R}}\delta[n] \tag{15}$$

where, $\tilde{V}_{BAT}$: reference voltage,
$\tilde{R}$: reference resistance

At the beginning of a given control period, the hardware controller calculated the solenoid resistance $R[n]$ by using Equation (14). It accumulated the calculated solenoid resistance over a fixed duration, e.g. one second, and updated the estimate of solenoid resistance $\hat{R}[n]$ once in a fixed duration, as shown by Equation (16). Because the accumulated resistance was sufficient to calculate the solenoid estimate $\hat{R}[n]$, it was not necessary to maintain the calculated solenoid resistance sequence. Therefore, required memory was only the accumulation of resistance estimates. Simultaneously, using the sample mean of

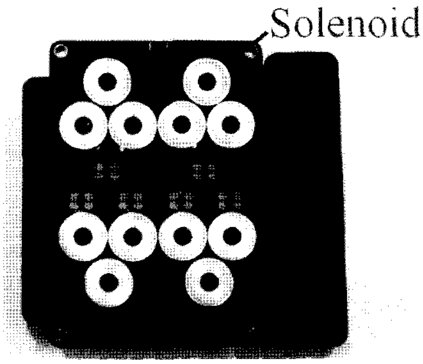


Figure 15. Solenoids installed on the HECU.

calculated solenoid resistances eliminated the effect of measurement noise factors.

$$\hat{R}[n]=\frac{1}{N}\sum_{k=n}^{n-N} R[k] \qquad (16)$$

Therefore, the proposed method satisfied the aforementioned new requirements:

- With the model of an average solenoid current, solenoid resistance was calculated in spite of continuous driving.
- By updating the estimate with the sample mean of the calculated solenoid resistances, the effects of measurement noise factors and modeling errors were eliminated.
- The equation of solenoid resistance was a simple polynomial expression which was implemented in integer operations. Furthermore, because the equation was calculated only once every control period, additional computational power requirements were very small.
- Because the proposed method maintained only an accumulation of the calculated solenoid resistances, additional memory requirements were very small.

6. EXPERIMENTAL RESULTS

Through several tests, it was confirmed that the proposed method represents a useful way to make hardware controllers robust with respect to temperature changes and noise factors.

6.1. Setting of Experiments

The micro-controller used in the experiments was the Freescale 6812DP256, a fixed-point 16-bit micro-controller which operated at 25 MHz. The PWM frequency was 20 kHz and the control period was 1msec. The circuit for current measurement consisted of a shunt resistor and an instrumental OP-AMP with an 80 dB CMRR (Common Mode Rejection Ratio). Figure 15 shows the solenoids installed on the EHB HECU (Hydraulic Electronic Control Unit).

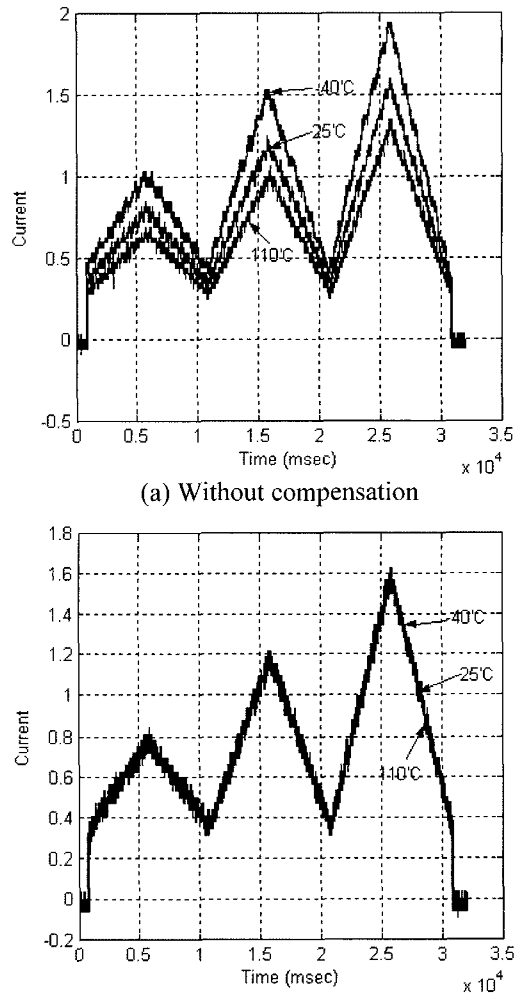


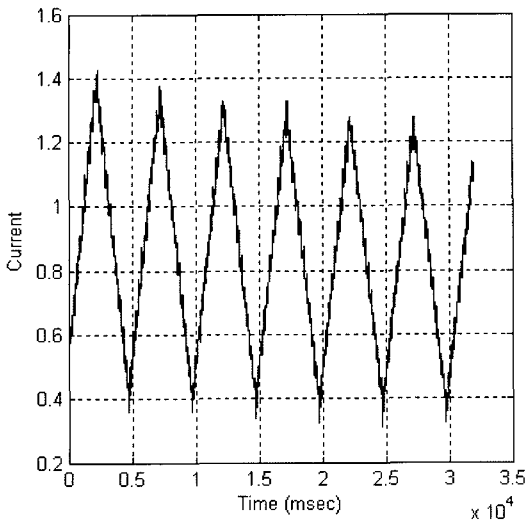
Figure 16. Invariance to ambient temperatures.

6.2. Invariance to Ambient Temperatures

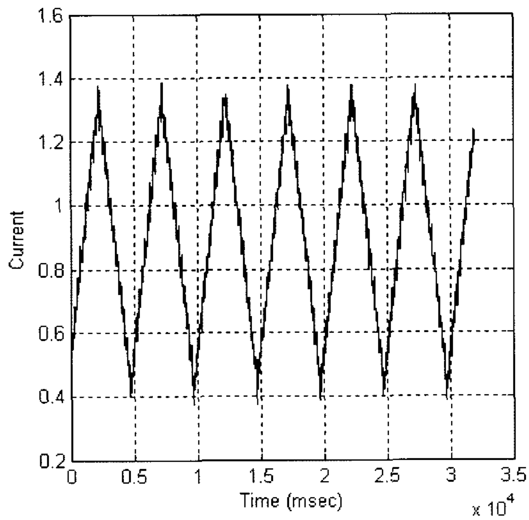
In constant temperature chambers, solenoids are driven by PWM duty ratio test patterns under three different temperature conditions: –40°C, 25°C, 110°C. Figure 16(a) shows the results of an uncompensated case. It can be observed that the patterns of the solenoid current differed from each other. Figure 16(b) shows the results of the compensated case. The patterns of the solenoid current were all the same in spite of different ambient temperatures.

6.3. Invariance to Continuous Driving

While driving a solenoid with a triangular PWM duty ratio pattern, the effect of resistance change caused by generated heat was investigated. Figure 17(a) shows the result of the uncompensated case. As the time passed by, the solenoid current decreased smoothly. Figure 17(b) shows the results of the compensated case. The pattern of



(a) Without compensation



(b) With compensation

Figure 17. Invariance to continuous driving.

the solenoid current did not change in spite of continuous driving.

7. CONCLUSION

This paper proposed a novel resistance estimation method of a PWM-driven solenoid. Simulation results showed that the proposed method was robust to noise and sufficiently fast to follow changing resistance. Experimental results showed that the proposed method was able to ensure a linear relationship between the PWM duty ratio and the solenoid current in spite of various ambient temperatures and resistance changes caused by generated heat. Therefore, this paper has presented three contributions. First, a simplified current model of the PWM-driven solenoid and its conditions, i.e. PWM frequency requirements, were derived. Second, the resistance of the PWM-driven solenoid was estimated based on the fixed point theorem. Third, the adaptive control method incorporating the estimation of a slow varying parameter, i.e. solenoid resistance, was more efficient and effective than direct control of a fast varying current.

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