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Adaptive Back-Stepping Control of Automotive Electronic Control Throttle

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Abstract

Back-stepping control (BSC), which is deemed effective for a non-holonomic system, is applied to improving both responsiveness and resolution performance of an electronic control throttle (ECT) used in automotive engines. This paper is characterized by the use of a two-step type BSC in a manner that achieves an improvement in responsiveness with the ETC operated in a fully opened state by adding a derivative term in Step 1 and the improvement in resolution performance with the ETC operated in a minutely opened state by adding an adaptive feature in the form of an integral term using the control deviation in Step 2. This paper presents an ECT control expressed as a second-order system including nonlinearities such as backlash of gear train and static friction in sliding area, a BSC system designed based on Lyapunov stability, and a determination method for control parameters. Also, a two-step type BSC system is formulated using Matlab/Simulink with a physics model as a control object. As a result of simulation analyses, it becomes clear that the BSC system can achieve quicker response because the derivative term works effectively and finer resolution because the adaptive control absorbs the error margin of the nonlinear compensation than conventional PID control.

Keywords

Back-Stepping Control, Adaptive Control, Electronic Throttle, Automotive Engine

1. Introduction

The electronic control throttle in automobile engine control systems is indispensable to increasing fuel economy and curbing exhaust emissions. It is the main actuator for torque control in gasoline engines and emission control in diesel engines, and its responsiveness and resolution have to meet strict requirements. It is anticipated that the electronic control throttle will not only provide a solution to relevant mechanical problems, but also deliver improvements through its method of control.

Research on nonlinear control based on feedback control enhanced by the Lyapunov design method has been in progress since the early 1990's. Krstić *et al.* proposed this type of control as "Back-stepping Design" [1], and Zhou *et al.* then systematized it as "Adaptive Back-stepping Control [2]". This back-stepping control (BSC) is a promising method applicable to electronic throttle control as a means of solving nonlinear problems, such as the backlash of the gear train and frictional characteristics of rotational sliding. Pan *et al.* proposed a relevant approach [3], but this focuses on state observers, and does not take advantage of the benefit obtained from BSC. The author *et al.* has achieved high responsiveness with the aid of sliding-mode control [4] [5]. However, nonlinear compensation for fine control is insufficient.

This paper describes a method for designing back-stepping control (BSC) of a low-order control object with the nonlinear characteristics expected for an automobile electronic control throttle. The control used is two-step type BSC based on a quadratic linear model so that design can be formulated in a manner similar to that for conventional PID control. We added a derivative control function to Step 1 in order to improve responsiveness, and an adaptive control function to Step 2 in order to absorb model errors in nonlinear compensation. The effects of these functions were examined by simulation using Matlab/Simulink. As control objects, we built a physical model based on the structure of the electronic control throttle, a backlash model for examining the drive torque, and a Stribeck model for consideration of frictional characteristics [6] [7]. The derivative term in Step 1 serves to improve the starting characteristics that the electronic control throttle exhibits in response to sudden acceleration. Minute opening control on the electronic control throttle may cause sticking due to static friction, overshooting after a motion, and a steady-state deviation due to backlash. The results of simulations suggest that such problems with resolution degradation due to response lag and nonlinear characteristics can be solved by improving Steps 1 and 2 of the two-step type BSC. We also achieved further improvement by referring to a reference linear model.

2. Basic BSC Design

This paper systematizes BSC design by assuming that the control object is an ($N \times N$) MISO system that combines the linear and nonlinear characteristics of a state variable. The control object is assumed to be an object described by Equation (1).

$$\begin{cases} \dot{x}_1 = \sum_{j=1}^{N} a_{1,j} x_j + \psi_1(\boldsymbol{x}) \\ \vdots \qquad \vdots \\ \dot{x}_i = \sum_{j=1}^{N} a_{i,j} x_j + \psi_i(\boldsymbol{x}) \\ \vdots \qquad \vdots \\ \dot{x}_N = \sum_{j=1}^{N} a_{N,j} x_j + \psi_N(\boldsymbol{x}) + b_N u \end{cases} \tag{1}$$

We designed an *N*-step control system that feeds back all the components of the state variable. The control law meeting the conditions for Lyapunov stability in each step is given by Equations (2) to (4). Derivation of these equations is omitted.

Step 1:

$$\alpha_1 = \frac{1}{a_{12}}\left(\dot{z}_d - c_1 z_1 - \sum_{j=1}^{N(j\neq 2)} a_{1j}x_j - \psi_1(\boldsymbol{x})\right) \tag{2}$$

Step i:

$$\alpha_i = \frac{1}{a_{i,i+1}}\left(\dot{\alpha}_{i-1} - c_i z_i - a_{i-1,i}z_{i-1} - \sum_{j=1}^{N(j\neq i+1)} a_{i,j}x_j - \psi_i(\boldsymbol{x})\right) \tag{3}$$

Step N:

$$u = \frac{1}{b_N}\left(\dot{\alpha}_{N-1} - c_N z_N - a_{N-1,N}z_{N-1} - \sum_{j=1}^{N} a_{Nj}x_j - \psi_N(\boldsymbol{x})\right) \tag{4}$$

where z_d is the desired value, and is the control error in Step i.

3. Modeling an Electronic Control Throttle

3.1. Linear Model

Figure 1 illustrates the structure of an electronic control throttle used for automobile engines. Its main elements are a DC motor, gear train (pinion gear, intermediate gear, and sector gear), butterfly valve, and springs. For these elements, a DC motor circuit equation, DC motor rotational motion equation, gear-train rotational motion equation, and valve rotational motion equation are derived. These physics are shown from Equations (5) to (8).

Table 1 shows the parameter names and their meanings used in the throttle valve's mathematical models. In addition, Equations (5) to (8) can be reduced to Equations (9) to (10) by considering the gear ratios.

$$L_m \frac{\mathrm{d}i}{\mathrm{d}t} + Ri + K_m \frac{\mathrm{d}\theta_m}{\mathrm{d}t} = V \tag{5}$$

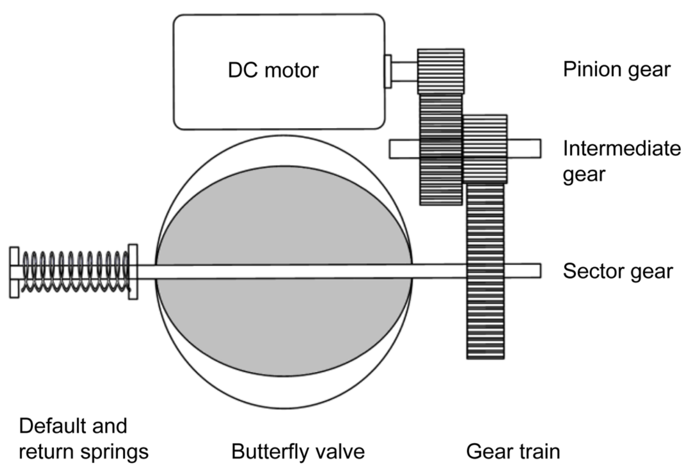

Figure 1. Structure of ECT.

Table 1. Parameters of ECT.

Parameters	Physical meanings	Units
θ_v	Valve opening	deg
θ_m	Motor rotary angle	deg
V	Motor voltage	V
T_{sp}, T_{spl}	Spring torque	-
N_g, N_v	Gear ratio	N·m
J_m, J_g, J_v	Moment of inertia	N·m·s^2
D_m, D_g, D_v	Viscous friction	N·m·s
E_g, E_v	Transmission efficiency	-
R	Motor internal resistance	Ω

$$J_m \frac{\mathrm{d}^2\theta_m}{\mathrm{d}t^2} + D_m \frac{\mathrm{d}\theta_m}{\mathrm{d}t} = K_m i - T_1 \tag{6}$$

$$J_g \frac{\mathrm{d}^2\theta_g}{\mathrm{d}t^2} + D_g \frac{\mathrm{d}\theta_g}{\mathrm{d}t} = N_g E_g T_1 - T_2 \tag{7}$$

$$J_v \frac{\mathrm{d}^2\theta_v}{\mathrm{d}t^2} + D_v \frac{\mathrm{d}\theta_v}{\mathrm{d}t} = N_v E_v T_2 - T_{sp}(\theta) \tag{8}$$

$$J \frac{\mathrm{d}^2\theta_v}{\mathrm{d}t^2} + D \frac{\mathrm{d}\theta_v}{\mathrm{d}t} + T_{sp}(\theta_v) = K \cdot I \tag{9}$$

$$L_m \frac{\mathrm{d}i}{\mathrm{d}t} + Ri + K_e \cdot N_g \cdot N_v \cdot \theta_v = V \tag{10}$$

where

$$\begin{aligned} J &= J_m \cdot N_g^2 \cdot N_v^2 \cdot E_g \cdot E_v + J_g \cdot N_v^2 \cdot E_v + J_v \\ D &= D_m \cdot N_g^2 \cdot N_v^2 \cdot E_g \cdot E_v + D_g \cdot N_v^2 \cdot E_v + D_v \\ K &= K_m \cdot N_g \cdot E_g \cdot N_v \cdot E_v \end{aligned}$$

3.2. Nonlinear Model

We consider the backlash characteristics described by **Figure 2** and Equation (11) and the friction characteristics described by **Figure 3** and Equation (12) as the nonlinear characteristics of the electronic control throttle. The friction characteristics are known as the Stribeck model and are obtained as a composite of static, Coulomb, and viscous friction. Since the viscous friction is already contained as the $D\dot{\theta}_v$ term of Equation (9), it is excluded when $T_{st}(\dot{\theta}_v)$ expressed by Equation (12) is applied.

$$\dot{T}_v(t) = \begin{cases} m\dot{T}_v(t) & \text{if } \dot{T}_v(t) \geq 0 \text{ and } T_v(t) = m\left(T_v(t) - B_r\right) \\ & \text{or if } \dot{T}_v(t) < 0 \text{ and } T_v(t) = m\left(T_v(t) - B_l\right) \\ 0 & \text{otherwise} \end{cases} \tag{11}$$

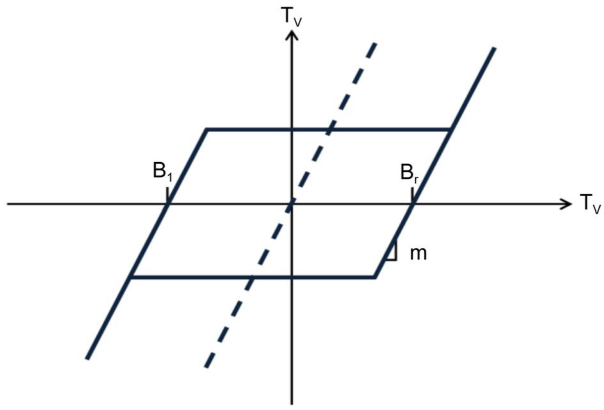

Figure 2. Backlash characteristics of gear train.

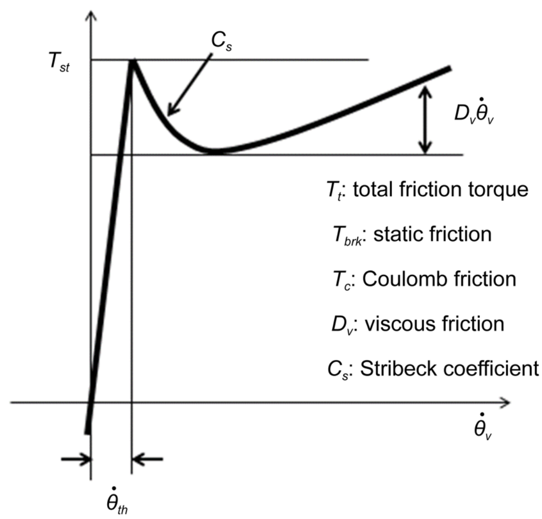

Figure 3. Stribeck friction nonlinearity.

$$T_{st}\left(\dot{\theta}_v\right)=\begin{cases}\text{if } \left|\dot{\theta}_v\right| \geq \dot{\theta}_{th} \\ \left(T_c+\left(T_{brk}-T_c\right)\exp\left(-c_s\left|\dot{\theta}_v\right|\right)\right) sign\left(\dot{\theta}_v\right)+D_v\dot{\theta}_v \\ \text{if } \left|\dot{\theta}_v\right| < \dot{\theta}_{th} \\ \left(\left(T_c+\left(T_{brk}-T_c\right)\exp\left(-c_s\left|\dot{\theta}_v\right|\right)\right)+D_v\dot{\theta}_v\right)\dot{\theta}_v \Big/ \dot{\theta}_{th}\end{cases} \tag{12}$$

3.3. Electronic Control Throttle

The block diagram in **Figure 4** is obtained by combining the linear model in 3.1 and nonlinear model in 3.2. As the physical model of an electronic control throttle, it is used as a control object in the creation of a control model or for confirming the performance of a control system.

3.4. Linear Control Model

A control model built directly from Equations (9) to (10) can be applied as a compensation model integrated into BSC. However, this paper derives a quadratic linear model in order to ensure consistency with conventional PID control systems. Assuming a control model expressed by Equation (13), we identified the step response of the electronic control model of Figure 4 with the nonlinear model excluded. We thereby obtained a second-order delay model that is in good agreement with the physical model, as can be seen in Figure 5.

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = a_{21}x_1 + a_{22}x_2 + b_2u \end{cases} \tag{13}$$

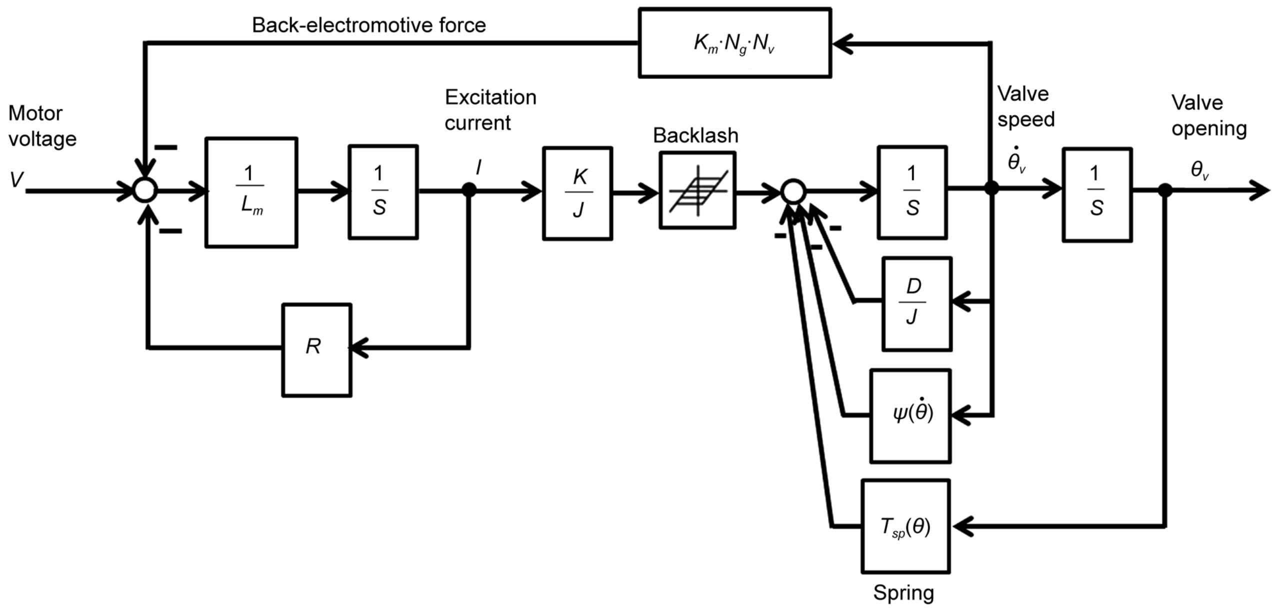

Figure 4. Block diagram of electronic control throttle.

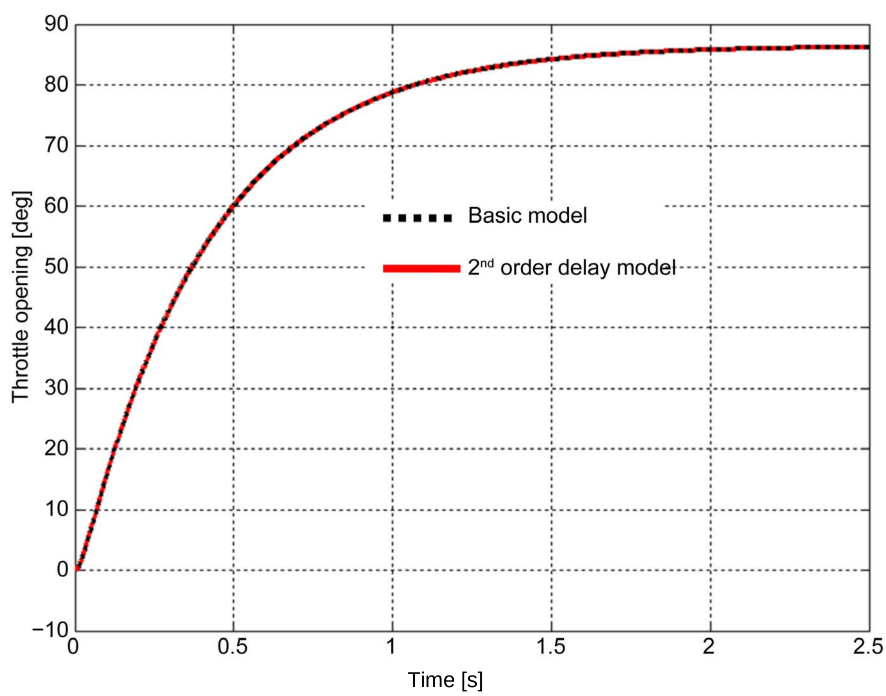

Figure 5. Fitting using 2nd order delay model of electronic control throttle.

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4. Detailed Design of BSC

When designing the BSC control system for the electronic control throttle, we changed the control object from Equation (1) to Equation (13) by reducing its order. This control object is a quadratic linear model suited to the control model derived in the preceding section with a friction and backlash model added. In the Equation (14), x_1 is the throttle opening, $\psi_2(x_2)$ the friction torque, and $B(\bullet)$ the backlash function.

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = \sum_{i=1}^{2} a_i x_i + \psi_2(x_2) + bu \\ u = B(v) \end{cases} \tag{14}$$

The BSC is a two-step type of control consisting of Step 1 for the x_1 feedback and Step 2 for the x_2 loop.

4.1. Adding a Derivative Term to Step 1

In this study, we added a derivative term to Step 1 in order to improve responsiveness (particularly the starting characteristics). The following demonstration of stability omits description of nonlinear characteristics.

Equation (15) defines the control law of Step 1 using a linear combination of a control deviation z_1 and its change rate $\dot{z}_1$.

$$\alpha_1 = z_d - (c_1 z_1 + d_1 \dot{z}_1) \quad (c_1 > 0 \quad d_1 \geq 0) \tag{15}$$

For the Lyapunov candidate function V_1 defined by Equation (15), we obtain:

$$V_1 = \frac{1}{2} z_1^2 \tag{16}$$

$$z_1 = x_1 - z_d \tag{17}$$

$$\dot{z}_1 = \dot{x}_1 - \dot{z}_d = x_2 - \dot{z}_d \tag{18}$$

$$\begin{aligned} \dot{V}_1 &= z_1 \dot{z}_1 = z_1 (x_2 - \dot{z}_d) \\ &= z_1 (x_2 - c_1 z_1 - d_1 \dot{z}_1 - \alpha_1) \\ &= -c_1 z_1^2 - d_1 z_1 \dot{z}_1 + z_1 (x_2 - \alpha_1) \\ &= -c_1 z_1^2 - d_1 \dot{V}_1 + z_1 z_2 \\ &= \frac{1}{1+d_1} (-c_1 z_1^2 + z_1 z_2) \end{aligned} \tag{19}$$

With Step 2 designed such that the intermediate control deviation $z_2 = 0$, the following inequality holds.

$$\dot{V}_1 \leq 0 \tag{20}$$

Since V_1 is a Lyapunov function, the control deviation z_1 converges to zero. For Step 2, the function V_2 of the intermediate control deviation z_2 defined by Equation (21) is selected as the Lyapunov candidate function.

$$V_2 = V_1 + \frac{1}{2\left(1+d_1\right)} z_2^2 \tag{21}$$

By differentiating both sides, we obtain the following.

$$\dot{V}_2 = \dot{V}_1 + \frac{z_2 \dot{z}_2}{\left(1+d_1\right)} = \frac{1}{\left(1+d_1\right)}\left(-c_1 z_1^2 - c_2 z_2^2\right) \le 0 \tag{22}$$

Since V_2 is a Lyapunov function, this inequality shows that Step 2 is stable, with the intermediate control deviation z_2 converging to zero.

Equation (22) is derived as follows.

$$\dot{V}_2 = \frac{1}{\left(1+d_1\right)}\left(-c_1 z_1^2 + z_1 z_2 + z_2 a_1 x_1 + z_2 a_2 x_2 + z_2 b u - z_2 \dot{\alpha}_1\right) \tag{23}$$

Assuming that the control law u is given by Equation (24), Equation (25) is obtained by substituting Equation (24) into Equation (21).

$$u = \frac{1}{b}\left(\dot{\alpha}_1 - c_2 z_2 - a_1 x_1 - a_2 x_2 - z_1\right) \ \left(c_2 > 0\right) \tag{24}$$

$$\begin{aligned} \dot{V}_2 &= \frac{1}{\left(1+d_1\right)}\left(-c_1 z_1^2 + z_1 z_2 + z_2 a_1 x_1 + z_2 a_2 x_2 - z_2 \dot{\alpha}_1 + z_2 b\left(\frac{1}{b}\left(-c_2 z_2 - z_1 - a_1 x_1 - a_2 x_2 + \dot{\alpha}_1\right)\right)\right) \\ &= \frac{1}{\left(1+d_1\right)}\left(-c_1 z_1^2 - c_2 z_2^2\right) \le 0 \end{aligned} \tag{25}$$

A stable control system can therefore be achieved by using Equation (24) as the control law for the BSC.

4.2. Adding an Integral Term to Step 2

Headings, or heads, are organizational devices that guide the reader through your paper. There are two types: Component heads and text heads.

As shown by Equations (2) and (3), BSC has the advantage of allowing nonlinear compensation to be easily achieved. When the friction function $\psi_2\left(x_2\right)$ is known, Equation (25) can be used as the control law for Step 2.

$$u = \frac{1}{b}\left(\dot{\alpha}_1 - c_2 z_2 - a_1 x_1 - a_2 x_2 - \psi_2 - z_1\right) \ \left(c_2 > 0\right) \tag{26}$$

In actual applications, however, nonlinear characteristics contain errors or are unknown. In addition, the backlash function $B(\bullet)$ and other characteristics need to be offset not by subtraction but with an inverse model. In this study, those issues were solved by adding an adaptive control term $f_{ad}\left(z_2\right)$ that integrates the control deviation z_2 in Step 2 under the conditions for Lyapunov stability. Equation (26) or (27) can be applied as the adaptive control term $f_{ad}\left(z_2\right)$.

$$f_{ad}\left(z_2\right) \triangleq z_2 \cdot \int \left|\varsigma\left(z_2 - z_2^*\right)\right| \mathrm{d}t \tag{27}$$

$$f_{ad}\left(z_2\right) \triangleq sign\left(z_2\right) \cdot \int \left|\eta\left(z_2 - z_2^*\right)\right| \mathrm{d}t \tag{28}$$

In these equations, z_2^* is the control deviation with respect to the reference linear model, but it is not always necessary within the allowable range of steady deviation. If an adaptive control term is added, the control law is given by Equation (29).

$$u = \frac{1}{b}\left(-\sum_{i=1}^{2} a_i x_i - c_2 z_2 - z_1 - \psi_2^* + \dot{\alpha}_1 - f_{ad}\right) \tag{29}$$

In this case, since Equation (27) can be expressed as Equation (30), stable control is guaranteed.

$$\dot{V}_2 = \frac{1}{(1+d_1)}\left(-c_1 z_1^2 - c_2 z_2^2 - z_2 f_{ad}\right) \le 0 \tag{30}$$

4.3. Adaptive BSC System

Figure 6 shows a block diagram of the adaptive back-stepping control system obtained from the above design. The backlash function is disregarded based on the following results of paragraph 5.3. The reference linear model in Figure 6 is the BSC system assumed without nonlinear control model and without parameter error margin of linear model and is not indispensable.

5. Simulations and Discussion

5.1. Improvement in Response

We examined the control performance of the BSC system by measuring the step response. Assuming that the control object has the physical characteristics shown in Figure 4, we used Matlab/Simulink and built the BSC system illustrated in Figure 6. The derivative term added to Step 1 improved the starting characteristics but delayed convergence near the desired value. To solve this

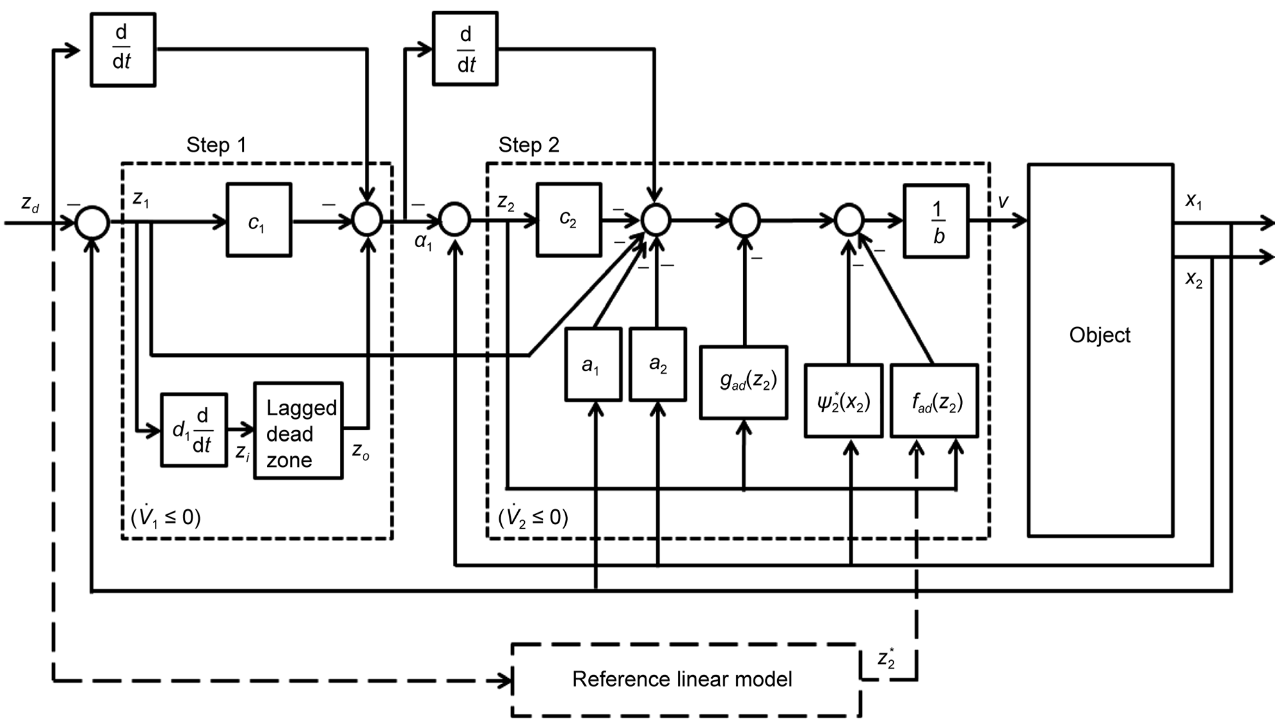

Figure 6. Two-step BSC system with adaptive control.

problem, we attached an imperfect dead zone expressed by Equation (31) to the subsequent stage of the derivative term (also included in Figure 6). This dead zone makes the control deviation z_1 minute and gradually reduces the derivative term gain. The Step 2 parameters a_1, a_2, b were determined by fitting the control object to Equation (11).

$$z_o(t) = z_i(t) + L\left(e^{-z_i(t)/L} - 1\right) \tag{31}$$

Figure 7 shows the results of the simulation. Response becomes higher with increasing derivative term gain in Step 1. This effect gradually becomes smaller, and the response does not exceed critical damping, so that no oscillation is observed.

5.2. Setting Control Parameters

The control parameters to be adjusted in designing the BSC are, in Step 1, the proportional term gain c_1 of the control deviation z_1 and the derivative term gain d_1, and, in Step 2, the proportional term gain c_2 of the intermediate control deviation z_2 and the parameters a_1, a_2, b of the linear control model expressed in Equation (13). The parameters a_1, a_2, b can be adjusted by fitting them to the step response of the control object. The proportional term gains c_1 and c_2, which are unique to the BSC, are mutually complementary, as shown in Table 2 which lists the simulation results. Hence, c_1c_2 is determined by considering factors such as the constraint on the operation quantity $u(t)$, and $\sup \dot{u}(t)$, the constraint on the controlled quantity x_1, and avoidance of overshoot. Next, c_1/c_2 is determined from the response speed of the controlled quantity x_1, for example, a 95% response in 80 ms. The remaining derivative term gain d_1 in Step 1 is determined by varying it from $d_1 = 0$ such that the target responsiveness is ensured under the above-mentioned constraints.

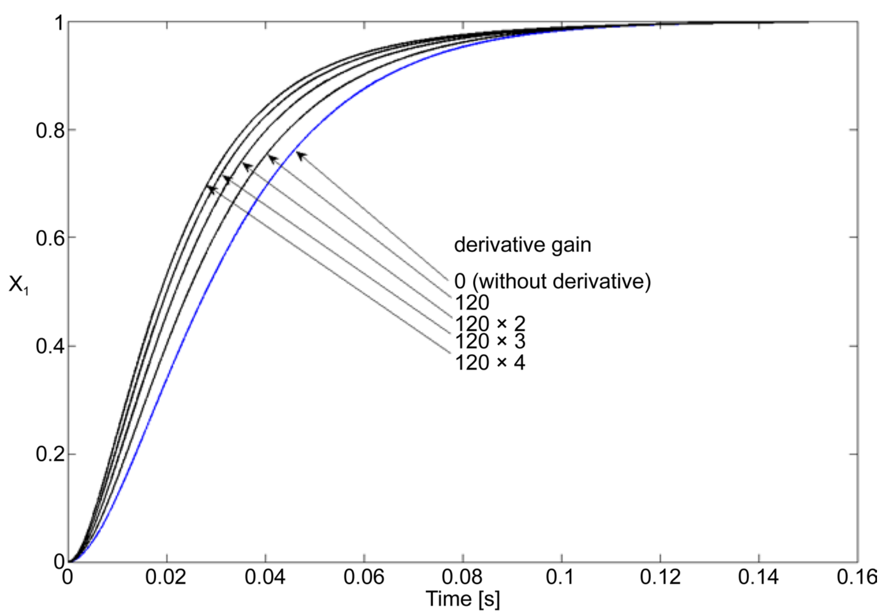

Figure 7. Effect in step response at derivative term.

5.3. Compensating for Backlash Characteristics

Backlash is included as Equation (11) in the control object. As shown in Equation (14), the relationship between the input u and output v of the control model is expressed as $u = B(v)$. This suggests that backlash compensation requires an inverse model. In this study, we assumed that the backlash was unknown and examined how effectively the adaptive control term $f_{ad}(z_2)$ absorbed it in Step 2. We implemented the simulation using Equation (32), which was obtained by omitting z_2^* from Equation (27).

$$f_{ad}(z_2) \triangleq z_2 \cdot \int |\varsigma \cdot z_2| \mathrm{d}t \tag{32}$$

Figure 8 shows the simulation results. As the backlash motion is repeated, the effect of the adaptive control term causes the motion to gradually approach that without backlash (*zd*). The results show that this tendency also differs depending on the BSC control parameter $c_1 \times c_2$. It can be seen that, when $c_1 \times c_2$ is sufficiently large relative to the width of the backlash dead zone, good responsiveness is obtained even without the adaptive control term.

5.4. Compensating for Friction Characteristics

Since the electronic control throttle needs to perform fine air-intake adjustment, the responsiveness to be achieved when the target degree of opening is changed

Table 2. Adjustment of control parameters.

Case	c_1	c_2	c_1/c_2	c_1c_2	Re s. at 80 ms
①	60	60	1.00	3600	95
②	45	80	0.56	3600	94
③	36	100	0.44	3600	93
④	30	120	0.36	3600	91
⑤	40	90	0.25	3600	88

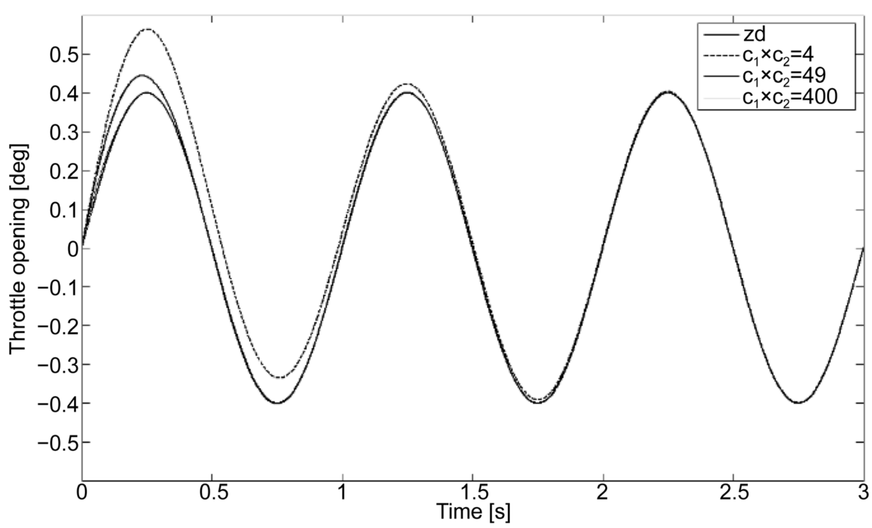

Figure 8. Behavior of adaptive control changing by design parameters.

on a continuous basis by 0.05˚ intervals is given as the target specification. In the operation of such minute openings (NOT: Narrow Open Throttle), friction characteristics have a relatively large influence. In this simulation, we used the friction compensation model $\psi_2^*(x_2)$ expressed by Equation (33).

$$\psi_2^*(x_2) = \xi \cdot \psi_2(x_2) \tag{33}$$

The friction characteristics are known when $\xi = 1$, contain an error when $1 > \xi > 0$, and are unknown when $\xi = 0$.

The simulation was implemented with a step response of 0.025˚, and includes the effect of adding the adaptive control term $f_{ad}(z_2)$. The results are given in Figure 9 and Figure 10.

Figure 9 shows the results corresponding to $\xi = 0.7$. It can be seen that the throttle does not operate without compensation for the static friction being applied. In addition, a large control deviation remains when compensation is implemented using only the friction compensation model $\psi_2^*(x_2)$. In contrast, the response is in close agreement with that corresponding to the no-friction state when the adaptive control term $f_{ad}(z_2)$ is added.

Figure 10 shows the results for $\xi = 0$, in which no friction compensation model is used since the friction characteristics are unknown. Although a steady deviation remains when only the adaptive control term $f_{ad}(z_2)$ is added, it can be reduced using the control deviation z_2 of Step 2 of the reference linear model.

5.5. Evaluating Electronic Throttle Control

Figure 11 shows the results of simulating operation of the electronic control throttle from the fully closed to fully open position (WOT: Wide Open Throttle), and compares it with operation using conventional PID control. All of the

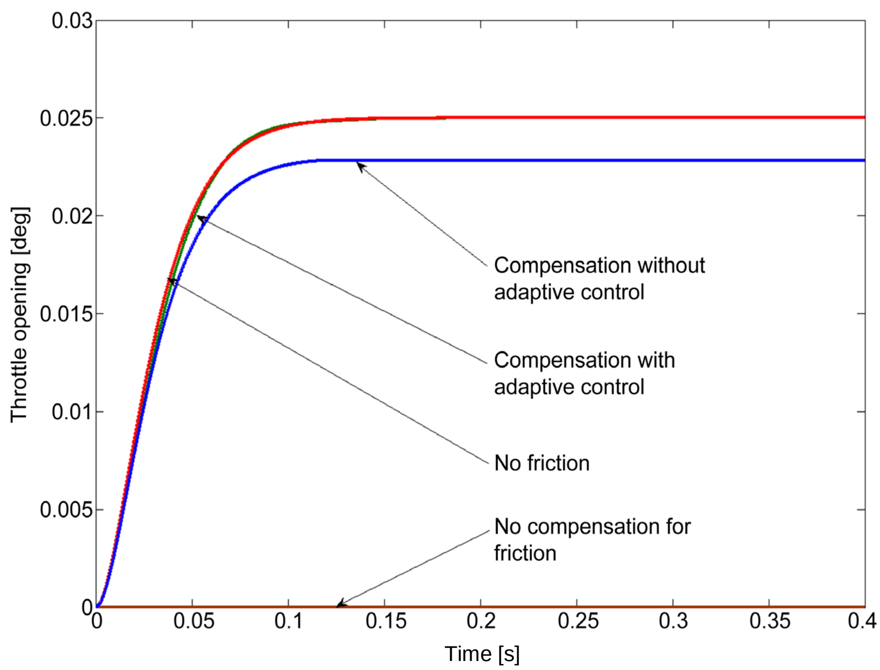

Figure 9. Responses when friction function contains error margin ($\xi = 0.7$).

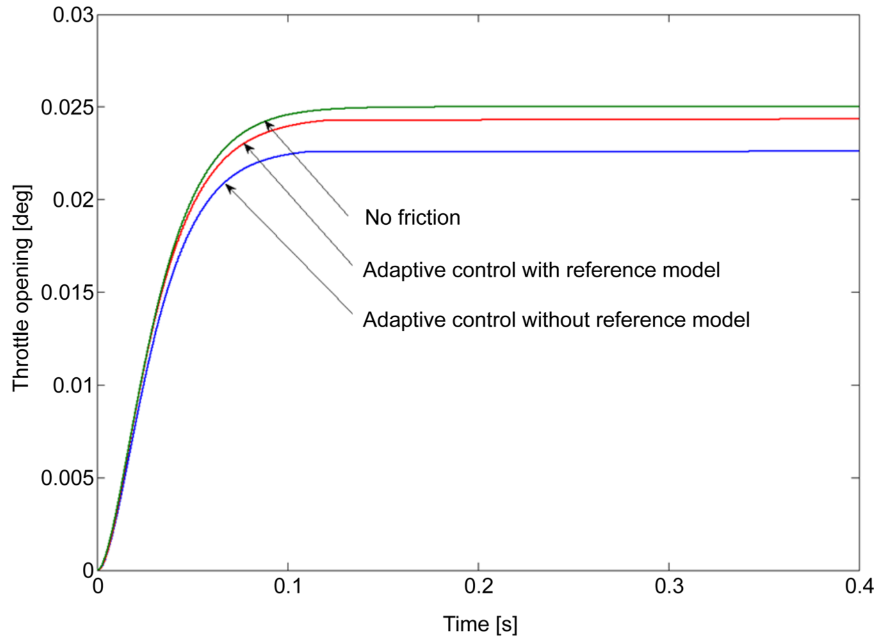

Figure 10. Responses when friction function is unknown ($\xi = 0$).

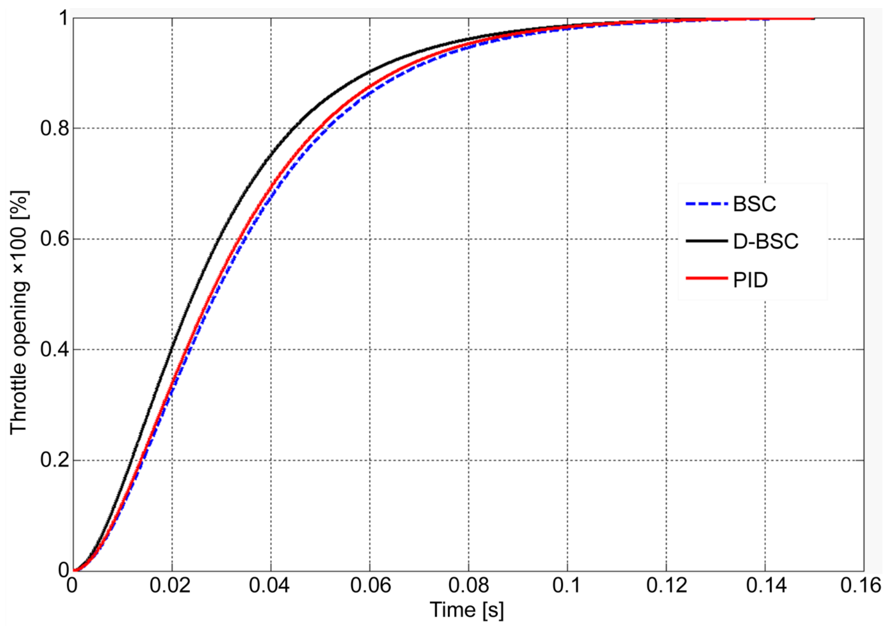

Figure 11. Test of Wide-Open-Throttle.

operations meet the 95% response in 80 ms required as the target specification. It can be seen that the starting characteristics are improved by adding a derivative term to Step 1 (D-BSC). Responsiveness can be adjusted by PID control, but too large a derivative term gain will cause overshooting. Critical damping is not exceeded with BSC.

Figure 12 shows the results of examining the resolution of the electronic control throttle. When its target degree of opening was changed on a continuous basis by 0.025˚ intervals, the setting value for PID control was affected by backlash

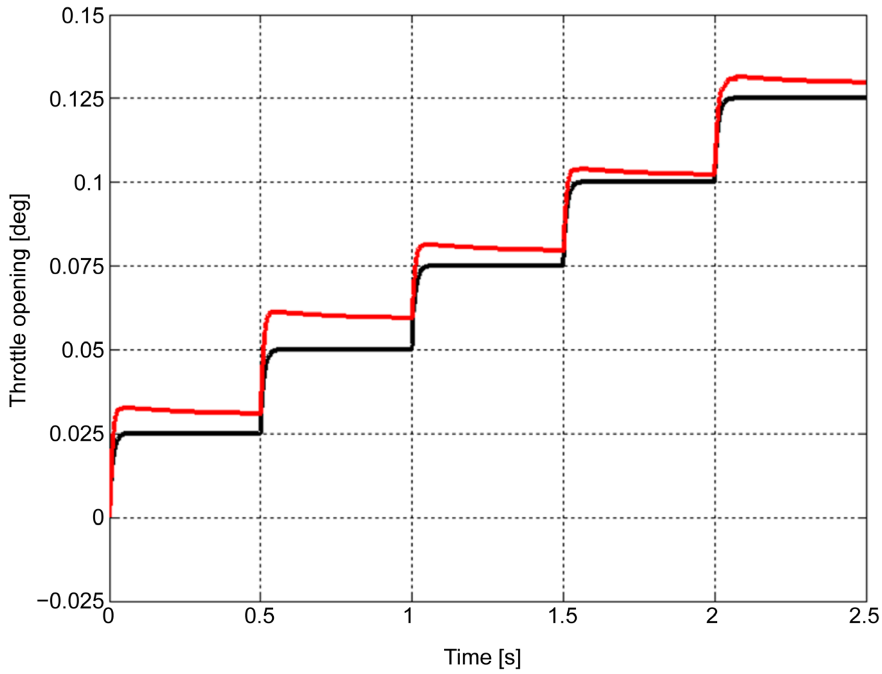

Figure 12. Test of Narrow-Open-Throttle.

and friction characteristics, making it indefinite. However, a resolution of 0.05˚ is required as the target specification of the equipment. In contrast, the effect of the compensation expressed by Equation (26) of Step 2 allows BSC to keep up with minute changes in the desired value.

6. Summary

Back-stepping control (BSC) can compensate separately for linear and nonlinear characteristics in the system design, and provide a stable response even when model errors are present. This study applied BSC to an electronic control throttle for automobiles, and thereby achieved improvements in both responsiveness and resolution performance. We expressed a general-purpose design method for BSC as Equations (1) to (4), and determined the following through the use of simulations.

(1) Two-step type BSC is suitable for electronic control throttles.

(2) We presented Equation (13) as the control law for a derivative term added to Step 1 of the two-step type BSC. This improves starting characteristics.

(3) We presented Equations (23) and (24) as control laws for an integral term added to Step 2 of the two-step type BSC (adaptive BSC). This absorbs errors that occur in nonlinear control models.

(4) Consideration of backlash compensation becomes unnecessary if the control gain ($c_1 \times c_2$) of the BSC is increased.

(5) Adaptive BSC allows the desired value to be followed even when friction characteristics are unclear ($\xi = 0.7$) or unknown ($\xi = 0$).

The above results indicate that electronic control throttles using the two-step type BSC that we have proposed can achieve a higher degree of responsiveness and resolution performance than conventional PID control.

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