Modelling and Observer-based Sliding-Mode Control of Electronic Throttle Systems

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ABSTRACT

With increasing demand for high fuel efficiency, better exhaust control measures, comfort and high performance on current automotive vehicles, electronic control of the throttle chamber which decides the engine output, is becomming advanced day by day. It is expected that this trend towards electronic control of the throttle chamber will be maintained in conjunction with injection air-amount control, drive control, traction control, etc. Modelling and control methods for electronic throttle servo systems are proposed, which consist of a DC motor, a throttle valve and a return spring. The control method fulfills the demand for high robustness in nonlinear opening of the throttle. In this paper, a modelling method of an electronic throttle chamber system is first proposed. Next, an observer-based sliding-mode controller with prescribed transient response is designed for the system. By using a function-augmented sliding hyperplane, it is guaranteed that the output tracking error converges to zero in a finite time. Simulation and experimental results demonstrate the effectiveness of the sliding-mode controller with prescribed transient response.

Keywords: Throttle Chamber, VSS Observer, Parameter Estimation, Genetic Algorithm, Function-Augmented Sliding-Mode Control.

1. INTRODUCTION

Fuel efficiency and exhaust control for automotive engines have been continually improved. Now, total control of engine and driving systems is progressing, with increasing demand for higher comfort and performance on current vehicles. Especially, electronic control of the throttle chamber which decides the engine output, is advancing day by day. This trend will continue towards electronic control of the throttle chamber in conjunction with injection air-amount control, drive control, traction control, etc [1, 2].

In this paper, a model-based control method for an electronic throttle system is proposed, which consists of a DC motor, a throttle valve and a return spring. The control method fulfills the demand for high robustness in nonlinear opening of the throttle. First, a model of an electronic throttle chamber system is built by using a genetic algorithm-based parameter estimation technique. Since the use of only the throttle angle is incomplete to improve the control performance, we propose a sliding-mode control (SMC) coupled with a nonlinear variable structure system (VSS) observer. This observer-based SMC is designed by using the function-augumented sliding hyperplane [3, 4]. This method guarantees that the output tracking error converges to zero in a finite time. As is known, when the system is in a sliding-mode (SM), there appears chattering of the control input and throttle angle. For avoiding this phenomenon, we propose a method of using a saturation function instead of a sign function. Simulation and experimental results are presented which confirm the effectiveness of the sliding-mode controller with prescribed transient response.

2. MODEL OF THROTTLE CHAMBER SYSTEM

For control design, it is of importance to know the characteristics of controlled object [5, 6]. First, we build a model of a throttle chamber system which is the controlled object (**Fig.1**) [7, 8].
The relation between current i_a and input voltage U_a in the armature circuit is described as

$$L\frac{di_a}{dt} + R_a i_a + K_e N\frac{d\theta}{dt} = U_a \tag{1}$$

where L and R_a are the inductance and registance in the circuit, respectively, K_e is the inductive voltage constant, N is the gear ratio, and θ is the throttle angle. Now, the electric-magnetic torque generated by the DC motor is given as $T = K_t i_a$. Then, we get

$$J\frac{d^2\theta}{dt^2} + D\frac{d\theta}{dt} + d_k\ \mathrm{sgn}(\frac{d\theta}{dt}) + K_s\theta = NK_t i_a \tag{2}$$

where J is the equivalent moment around the throttle axis, D is the frictional coefficient, and K_s is the re-

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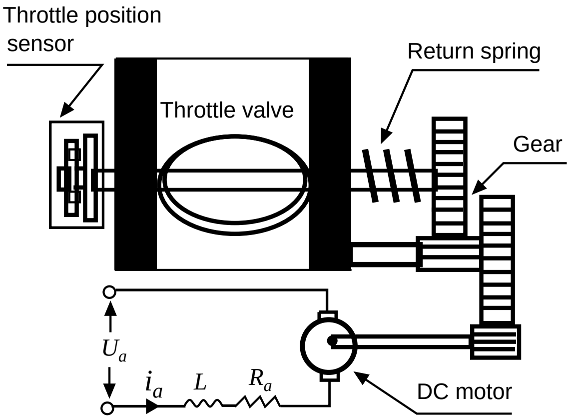

Fig.1: *The conceptual joint system model.*

turn spring constant. Ignoring the inductance L, we have the following equation by substituting (1) into (2):

$$\begin{aligned}\ddot{\theta} \;&=\; -\frac{1}{J}(D+\frac{N^2K_tK_e}{R_a})\dot{\theta}-\frac{1}{J}d_k\ \mathrm{sgn}(\dot{\theta})\\ &\quad -\frac{1}{J}K_s\theta+\frac{NK_t}{R_aJ}U_a \end{aligned} \tag{3}$$

Defining the state variables as $x_1=\theta$ and $x_2=\dot{\theta}$ in (3), we have the state and output equations:

$$\begin{aligned}\begin{bmatrix}\dot{x}_1\\ \dot{x}_2\end{bmatrix} &= \begin{bmatrix}x_2\\ a_1x_1+a_2\ \mathrm{sgn}(x_2)+a_3x_2\end{bmatrix}\\ &+ \begin{bmatrix}b_1\\ b_2\end{bmatrix}U_a\end{aligned} \tag{4}$$

$$y=x_1 \tag{5}$$

where $a_1=-(K_s)/J$,$a_2=-d_k/J$, $a_3=-(D/J+(N^2K_t/K_e)/(R_aJ))$, $b_1=0$, and $b_2=NK_t/R_aJ$.

3. DESIGN OF MODEL-BASED CONTROL SYSTEMS

3.1 Design of Nonlinear VSS Observer and Model Identification

As usual, we suppose that the throttle angel θ is the only measurement output defined as x_1. Therefore, we have to design an observer for state-feedback control design. First, we simply rewrite (4) and (5) in the form

$$\dot{x}=f(x)+b\ U_a \tag{6}$$

$$y=c^Tx \tag{7}$$

where

$$x=[x_1\ \ x_2]^T \tag{8}$$

$$f(x)=\begin{bmatrix}x_2\\ a_1x_1+a_2\ \mathrm{sgn}(x_2)+a_3x_2\end{bmatrix}$$

$$b=[0\ \ b_2]^T,\quad c=[1\ \ 0]^T$$

For this nonlinear system, we design the following robust VSS observer which can estimate all the state variables [9, 10]:

$$\dot{\hat{x}}=f(\hat{x})+b\ U_a+b\ \zeta\ \mathrm{sgn}(\bar{y})+k\ \bar{y} \tag{9}$$

$$\bar{y}=\hat{y}-y=c^T(\hat{x}-x) \tag{10}$$

where $\hat{x}$ is the estimate of state, $k=[k_1\ \ k_2]^T$ is the observer gain, b sgn($\bar{y}$) is the nonlinearity compensation term for observer, ζ is a scalar gain, and

$$\mathrm{sgn}(\bar{y})=1 \text{ if } \bar{y}>0\quad 0 \text{ if } \bar{y}=0\quad -1 \text{ if } \bar{y}<0 \tag{11}$$

@ Setting

$$\bar{x}=\hat{x}-x \tag{12}$$

we have the error system such as

$$\dot{\bar{x}}=f(\hat{x})-f(x)+k\ c^T\ \bar{x}+b\ c^T\zeta\ \mathrm{sgn}(\bar{x}) \tag{13}$$

Here, the observer gain k is designed to stabilize (13) by minimizing

$$J_o=\int_0^{T_o}\bar{y}^2(t)dt \tag{14}$$

This is just a class of nonlinear optimization problem. Thus, we propose a method for simultaneously estimating the observer gain k and unknown physical parameters a_1, a_2, a_3, b_2 by using a genetic algorithm (GA) [11] based on (14). As well known, a GA is applicable to a black-box optimization problem without a prior information. In our problem, there are non-differentiability of the fitness function (16) and sign constraints on physical parameters. First, we randomly assign 72 bits to six individuals $a_1, a_2, a_3, b_2, k_1, k_2$, and randomly generate 30 initial sequences in the same manner. The model output is made by using pseudo-random (M-sequence) signals as U_a inputted to the observer. The detailed GA procedure to be taken here is omitted due to lack of space [12]. The estimated results are listed in **Table 1**.

Table 1: *Estimated Observer Gain & Parameters*

symbols	values
a_1	-1.024 $\times 10^1$
a_2	-0.295
a_3	-7.565 $\times 10^1$
b_2	5.378 $\times 10^2$
k_1	-7.065 $\times 10^2$
k_2	1.028

3.2 Design of Slidng-Mode Control Systems

As is known, the robustness of SMC is a most outstanding feature. The differential equation describing the sliding hyperplane makes it possible to remove the influence of modelling error (identification error) and unmeasurable external input (disturbance) under the matching condition. If designing a hyperplane as the desired output trajectory, we can adapt the output to the desired one. Our purpose is to move the initial state onto the hyperplane, and to the stable equilibrium point. Here, all the linear control theory can be used to design the hyperplane [13, 14].

Besed on the state vector estimated by the VSS observer, we define a function-augumented sliding hyperplane [3, 4] as

$$s(t) = s_1e(t) + s_2\dot{e}(t) - z(t) \quad (15)$$

$$e(t) = x_1(t) - x_d(t) \quad (16)$$

where $x_d(t)$ is a twice continuously differentiable function describing the reference trajectory (reference output), and s_1 and s_2 are positive constants.

$$z(t) = s_1q(t) + s_2\dot{q}(t) \quad (17)$$

The function $q(t)$ in (19) is called "augment function", and is designed on the interval $[0, t_f]$, $t_f > 0$ (see (27)). By using $s(t)$ in (17), we conclude that the input

$$\begin{aligned} U_a &= K_p[-s_1\dot{e} + s_2(\ddot{x}_d - a_1x_1 - a_2 \text{ sgn}(x_2) \\ &- a_3x_2) + s_1\dot{q} + s_2\ddot{q} - P \text{ sgn}(s)] \end{aligned} \quad (18)$$

transfer the state onto the sliding hyperplane ($s(t) = 0$, $t > 0$). In (20),

$$\begin{aligned} P &= \delta|s_1\dot{e} - s_2\ddot{x}_d + s_2(a_1x_1 + a_2 \text{ sgn}(x_2) \\ &+ a_3x_2) - s_1\dot{q} - s_2\ddot{q}| + \eta \end{aligned} \quad (19)$$

$$\text{sgn}(s) = 1 \; if \{ s > 0 \quad 0 \; if \; s = 0 \quad -1 \; if \; s < 0 \quad (20)$$

where $\eta > 0$C$K_p > 0$ and $\delta > 0$.

Here, we define a Lyapunov function regarding a hyperplane s as

$$V = \frac{1}{2}s^2 \quad (21)$$

Eventually, we have

$$\begin{aligned} \dot{V} &= s\dot{s} = s(s_1\dot{e} + s_2\dot{x}_2 - s_2\ddot{x}_d - \dot{z}) \\ &= s[s_1\dot{e} - s_2\ddot{x}_2 - \dot{z} \\ &\quad +s_2(a_1x_1 + a_2 \text{ sgn}(x_2) + a_3x_2 + b_2U_a)] \\ &= s\{s_1\dot{e} - s_2\ddot{x}_2 - \dot{z} \\ &\quad +s_2(a_1x_1 + a_2 \text{ sgn}(x_2) + a_3x_2) \\ &\quad +\beta[-s_1\dot{e} + s_2\ddot{x}_d + \dot{z} - s_2a_1x_1 \\ &\quad -s_2a_2 \text{ sgn}(x_2) - s_2a_3x_2 - P \text{ sgn}(s)]\} \\ &= s[(1-\beta)(s_1\dot{e} - s_2\ddot{x}_d - \dot{z} + s_2a_1x_1 \\ &+ s_2a_2 \text{ sgn}(x_2) + s_2a_3x_2) - \beta P \text{ sgn}(s)]\} \end{aligned} \quad (22)$$

where $\beta = K_ps_2b_2 > 0$. Then, selecting δ so as to $\delta > |\beta - 1|/\beta$, (22) can be rewritten in the form

$$\begin{aligned} \dot{V} &= s[(1-\beta)(s_1\dot{e} - s_2\ddot{x}_d - s_1\dot{q} - s_2\ddot{q} + s_2a_1x_1 \\ &+ s_2a_2 \text{ sgn}(x_2) + s_2a_3x_2) - \beta\delta|s_1\dot{e} - s_2\ddot{x}_d \\ &+ s_2a_1x_1 + s_2a_2 \text{ sgn}(x_2) + s_2a_3x_2 \\ &- s_1\dot{q} - s_2\ddot{q}| \text{ sgn}(s) - \beta\eta \text{ sgn}(s)] \\ &< -\beta\eta|s| \end{aligned} \quad (23)$$

This inequality means that (18) gives a stable SMC.

The control parameters s_1, s_2, K_p, δ and η are designed by minimizing

$$J_c = \int_0^{T_c} |e(t)|dt \quad (24)$$

The minimization is performed by using the GA based on the fitnesss function (24). Lastly, we get $s_1 = 10.872$C$s_2 = 0.278$C$K_p = 0.142$C $\delta = 5.802$, and $\eta = 0.325$. **Fig.2** shows a block diagram of the designed control systems.

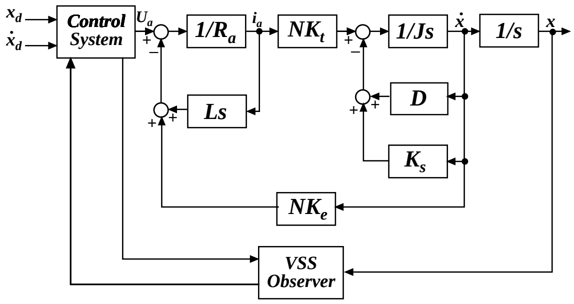

Fig.2: *The conceptual joint system model.*

4. SIMULATION AND EXPERIMENTAL RESULTS

4.1 Simulation and Experimental Conditions

We show simulation results for confirmation of the effectiveness of SM controller with VSS observer. In our simulation and experiments, the sampling period of input/output signal is $\Delta t = 0.4$ [ms], the integral intervals in (16) and (24) are $T_o = T_c = 5$ [s], the initial states are $x_1(0) = 5.0$ [deg] and $x_2(0) = 0$ [deg/s], the desired angle is $x_d = 60.0$ [deg], the desired angular velocity is $\dot{x}_d = 0$ [deg/s], the control time for the desired angle is $t_f = 0.4$ [s], and the scalar gain is $\zeta = 1.250$.

The augment function $q(t)$ used in the sliding hyperplane is defined as

$$q(t) = \begin{cases} v_0 + v_1t + v_2t^2 + v_3t^3 & if \;\; 0 < t < t_f \\ 0 & if \;\; t \geq t_f \end{cases} \quad (25)$$

where $v_0 = e(0)$, $v_1 = \dot{e}(0)$, $v_2 = -3v_0/t_f^2 - 2v_1/t_f$ and $v_3 = 2v_0/t_f^3 + v_1/t_f^2$. For example, $q(t)$ is selected as an output trajectory function to be given freely by control system designers. In the experiments in 4.3, it has to be set as $t_f > 0.23$ [s] when considering the system's time constant.

4.2 Simulation Results

Fig.3 and **Fig.4** show the throttle angle x_1 and its velocity x_2, and the corresponding phase portrait ($x_1 - x_2$) when using a sgn-function. **Fig.5** shows the control input U_a with a sgn-function. From these

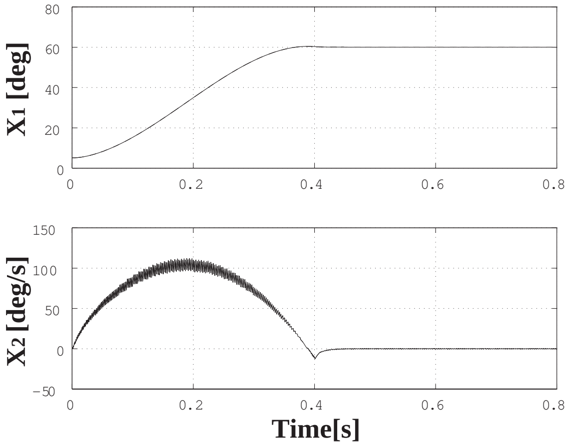

Fig.3: *The conceptual joint system model.*

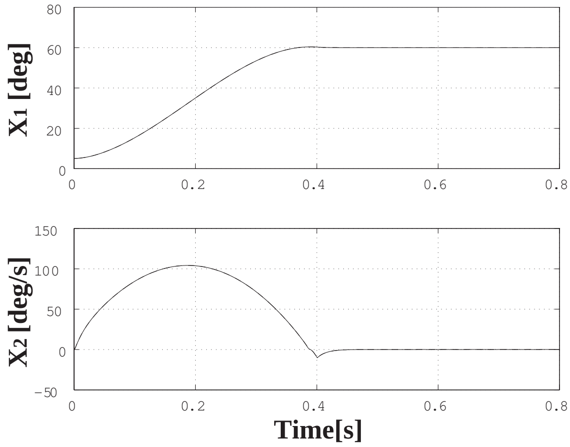

Fig.6: *The conceptual joint system model.*

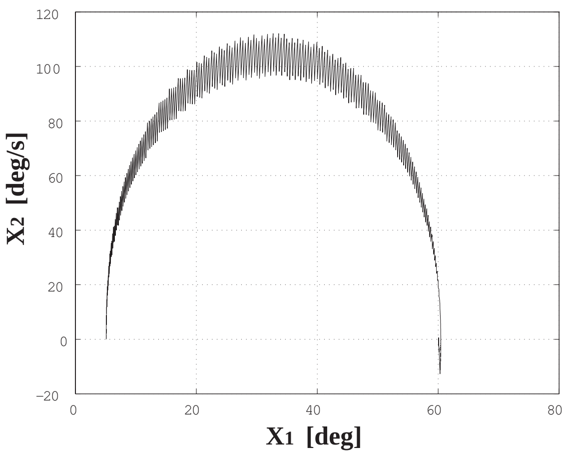

Fig.4: *The conceptual joint system model.*

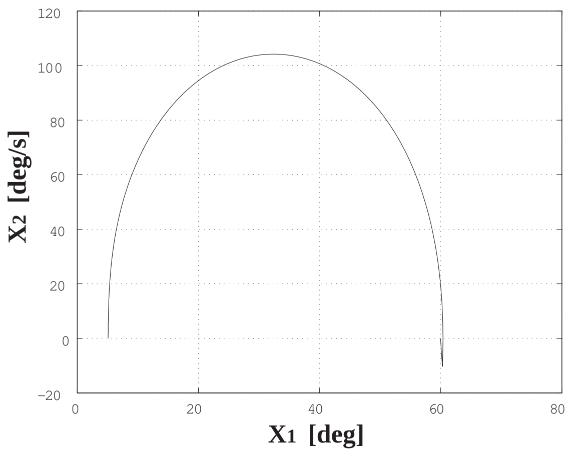

Fig.7: *The conceptual joint system model.*

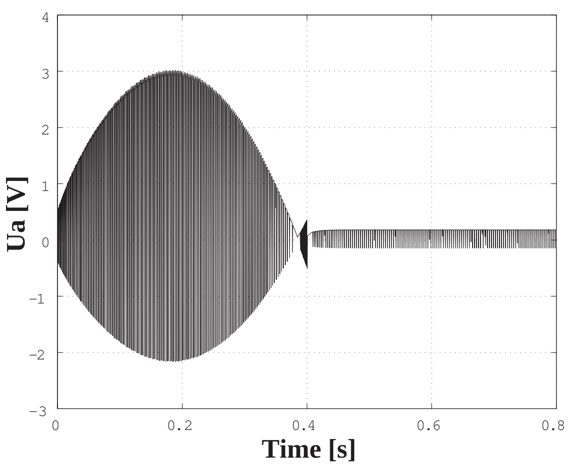

Fig.5: *The conceptual joint system model.*

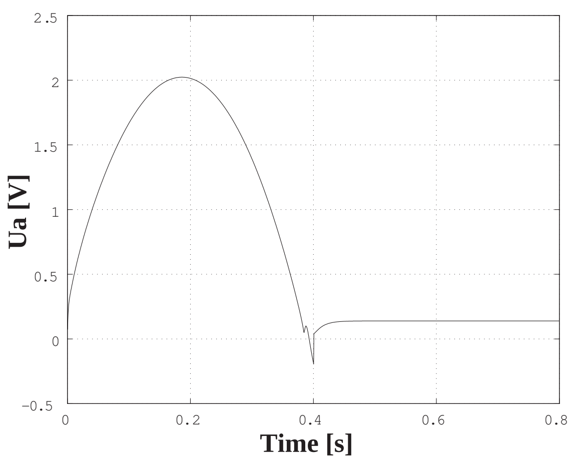

Fig.8: *The conceptual joint system model.*

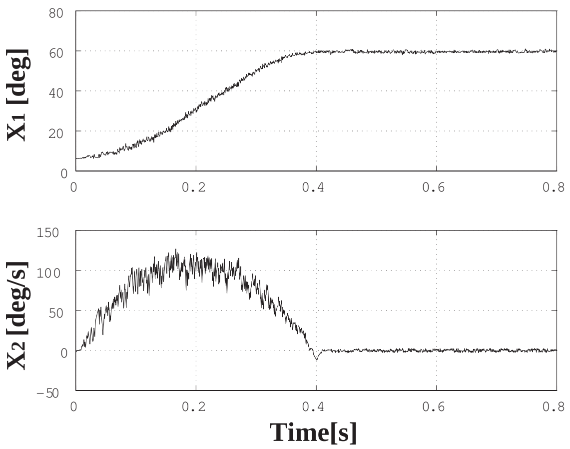

Fig.9: *The conceptual joint system model.*

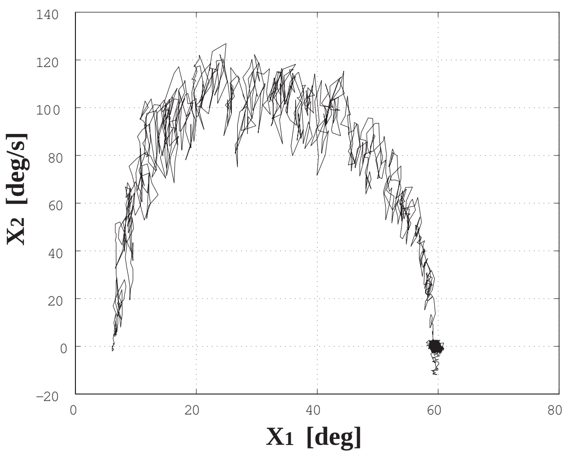

Fig.10: *The conceptual joint system model.*

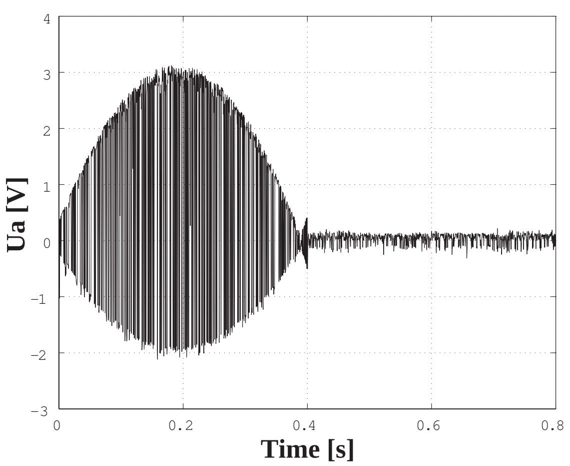

Fig.11: *The conceptual joint system model.*

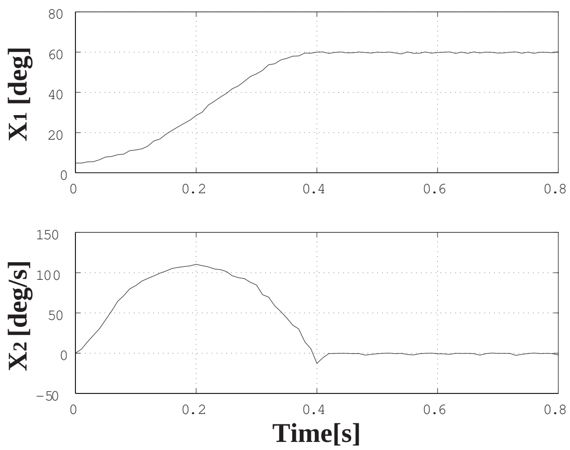

Fig.12: *The conceptual joint system model.*

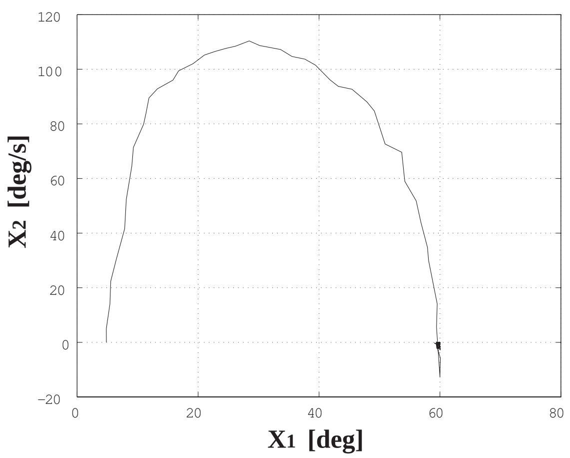

Fig.13: *The conceptual joint system model.*

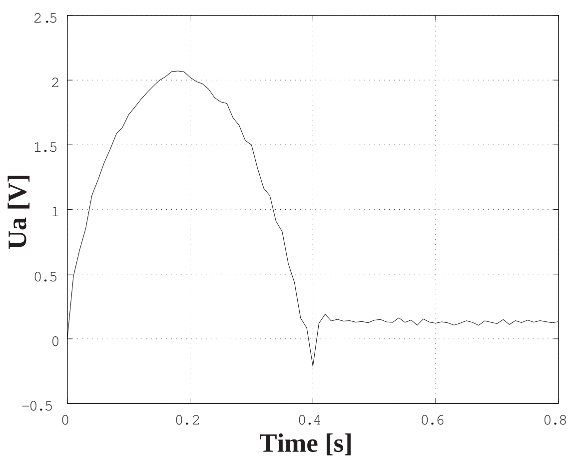

Fig.14: *The conceptual joint system model.*

simulation results, the throttle angle and its velocity converge to the desired angle and velocity within a prescribed control time (0.4[s]). But, it is obvious that chattering of control input makes the throttle valve oscillating with high frequency. This is because the switching time (sampling period) Δt is finite in practice. For removing the chattering, we introduce a saturation function (sat-function) instead of a sgn-function.

$$\mathrm{sat}(s) = \mathrm{sgn}(s) \quad if \quad |s| > \phi \quad s/\phi \quad if \quad |s| \leq \phi \quad (26)$$

where ϕ is a positive constant for surppressing chattering.

Fig.6 and **Fig.7** show the throttle angle and its velocity, and the corresponding phase portrait using a sat-function, respectively. **Fig.8** shows the control input when using a sat-function. From these results, it turns out that the throttle angle and its velocity converge smoothly to the desired values without input chattering. That is, the proposed SMC systems are practically stable.

4.3 Experimental Results

The experiments are executed under the same condition as that in simulation.

Fig.9, **Fig.10** and **Fig.11** show the throttle angle and its velocity, the corresponding phase portrait and control input, respectively. As you can see, the throttle angle and its velocity converge to the desired values in the prescribed time. But, you can also observe chattering which makes the control input and throttle angle oscillating seriously. We here adopt a sat-function as in the simulation.

Fig.12, **Fig.13** and **Fig.14** show the throttle angle and its velocity, phase portrait and control input, respectively. It turns out that almost the same results are obtined as those in the simulation. That is, we can give a successful control performance without input chattering and output overshoot.

5. CONCLUSIONS

In this paper, a modelling method for an electronic throttle system was proposed, and a new SMC method for positional servoing of the system was proposed. We were able to show that the output trajectory error converges to zero without input chattering and output overshoot within a prescribed control time by using the function-augumented sliding hyperplane.

There remains the theoretical problem of stability of observer-based SMC systems for this type of controlled object. Furthermore, actual throttle chamber systems have mechanical non-linearities of the return-spring constant, throttle angle, etc. Therefore, it is necessary to build a more precise model of throttle chamber with consideration of these factors and to design an SMC based on the identified model.

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