

# Accurate Engine Speed Control Using Sliding Mode Algorithm

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## ABSTRACT

Accurate engine speed control has been required to improve the shift quality of automatic transmissions. However, engine dynamics dramatically change with engine load and with engine aging. Therefore, conventional controls such as PID control cause large overshoots and therefore cannot ensure accurate controllability. A control composed of a sliding-mode controller and an adaptive disturbance observer was designed and applied to engine speed control to address these issues. The new control had high robustness against changes in engine dynamics and excellent ability to suppress overshoot. In addition, it provided accurate and rapid engine speed control under all engine conditions.

## 1. Introduction

Accurate and rapid engine speed control is increasingly required to improve the shift quality of automatic transmissions. However, engine dynamics dramatically change with engine load and with engine aging. Variations between similar engines will produce different engine dynamics also. Therefore, engine speed control requires robustness against these changes.

However, most conventional engine speed control has been open loop control using tables and maps or PID control. Figure 1 shows the results of engine speed control using PI control. Here, the engine speed  $N_e$  overshoots the target value  $N_{er}$  by a significant margin. This indicates that conventional control cannot achieve sufficient controllability.

On the other hand, sliding mode control<sup>(1)</sup>, which is a type of robust control, has been applied to engines<sup>(2), (3)</sup> and other

devices<sup>(4)</sup> in recent years.

Therefore, a new control method composed of a sliding-mode controller (SMC) and an adaptive disturbance observer was designed, and applied to engine speed control in this research.

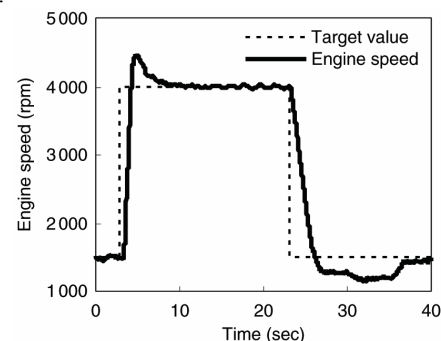


Fig. 1 Step response result using PI controller

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## 2. Engine Speed Control Challenges

Table 1 shows the specifications of the prototype engine used for the vehicle tests, and Fig. 2 shows the throttle angle  $T_h$  used to regulate the engine speed  $N_e$  to each  $N_{er}$  value. This figure shows a correlation between  $N_e$  and  $T_h$  in accordance with the electrical load level and the engine warm-up condition, but the  $T_h$  needed to regulate each  $N_{er}$  varies widely. For example, when  $T_h$  is around 8 degrees,  $N_e$  is approximately 4 000 rpm at a low electrical load, or approximately 3 000 rpm at a high electrical load.

This means that conventional open loop control may cause a significant steady-state error depending on the load conditions. A control method using scheduled maps and tables according to the engine load and warm-up condition can also be employed, but it cannot compensate for steady-state error caused by the engine torque characteristic changes from aging and variation between similar engines.

On the other hand, when PID control and adaptive sliding mode control<sup>(2)</sup>, which are types of closed loop controls, are applied to engine speed control, the steady-state error of  $N_e$  from  $N_{er}$  can be compensated.

However, each of these methods uses an integrator to suppress the steady-state error, so overshoot occurs as shown in Fig. 1.

Table 1 Specifications of experimental power train

|              |                                       |
|--------------|---------------------------------------|
| Engine       | In-line 3, 1.0 liter, SOHC            |
| Air device   | Electrical controlled throttle        |
| Transmission | 6-speed automated manual transmission |

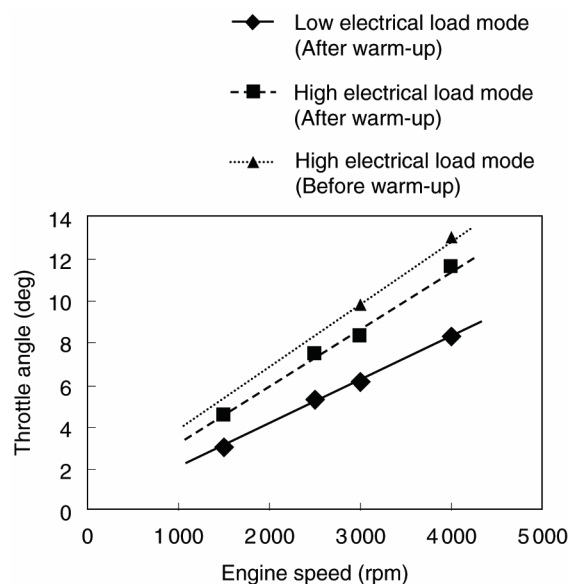


Fig. 2 Correlation of throttle angle with engine speed under several load conditions

## 3. Approach

A control system that can compensate for steady-state error caused by changes in engine dynamics due to aging condition and variation, while at the same time suppressing overshoot, was constructed as follows.

First, the engine dynamics from  $T_h$  to  $N_e$  were modeled not by using maps and tables, but by focusing on frequency characteristics and using a discrete-time auto-regressive exogenous (ARX) model<sup>(5)</sup>.

Next, the adaptive sliding mode control input was calculated as the sum of the three inputs of the equivalent control input  $U_{eq}$ , reaching law input  $U_{rch}$  and adaptive law input  $U_{adp}$  as shown in Fig. 3. Here,  $U_{eq}$  is calculated based on  $N_e$  and  $N_{er}$ , and  $U_{rch}$  and  $U_{adp}$  are calculated as the proportional element and integral element, respectively, of the switching function  $\sigma$  which is calculated according to the error between  $N_e$  and  $N_{er}$ . In addition,  $U_{adp}$  functions to compensate for changes in the engine dynamics, but since  $U_{adp}$  is the integral element of  $\sigma$ , it is also a cause of  $N_e$  overshoot relative to  $N_{er}$ .

Therefore, this research eliminated  $U_{adp}$  from the sliding-mode controller in Fig. 3 and added an adaptive disturbance observer in its place that calculates the estimated disturbance value ( $c_1$ ) based on  $N_e$  and the control input. In addition, the  $U_{eq}$  calculation formula was changed to include  $c_1$  in order to compensate for changes in the engine dynamics. Figure 4 shows the configuration of this new sliding-mode controller, and the details are described below.

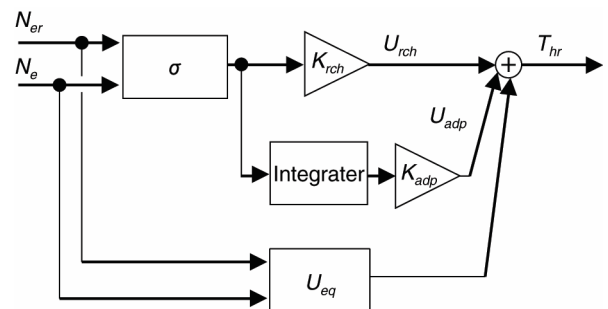


Fig.3 Sliding-mode controller with adaptive law input

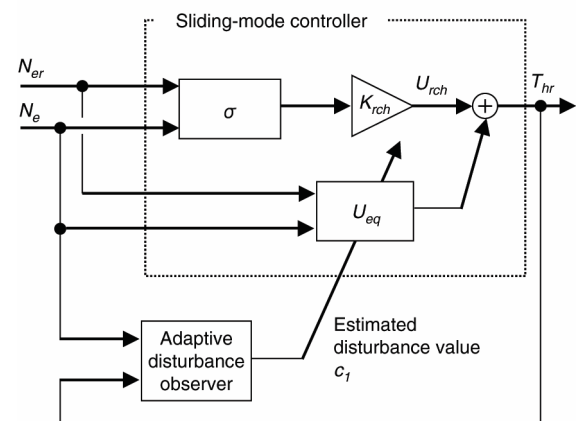


Fig.4 Sliding-mode controller with adaptive disturbance observer

## 4. Controller Design

### 4.1. Modeling of the Engine

Figure 5 shows the  $N_e$  response characteristics relative to changes in  $T_{hr}$ , in other words the engine frequency characteristics, at 1 500, 2 000, and 3 000 rpm. As shown in this figure, the engine frequency characteristics indicate low-pass characteristics, the gains of which are decreased at frequencies above 1.0 Hz. The gains of the frequency characteristics at passband frequencies are increased according to increases of  $N_e$ .

Based on these observations, the engine was modeled using the following equation.

$$N_e(k+1) = a_1 N_e(k) + a_2 N_e(k-1) + b_1 T_{hr}(k) + b_2 T_{hr}(k-1) \quad (1)$$

$a_1, a_2, b_1, b_2$  : Model parameters  
 $T_{hr}$  : Throttle target value  
 $k$  : Control time

Figure 6 shows the frequency characteristics of the engine and the model using the model parameters shown in Table 2 at 1 500 rpm. This shows that the model is able to accurately express the low-pass characteristics of the controlled object.

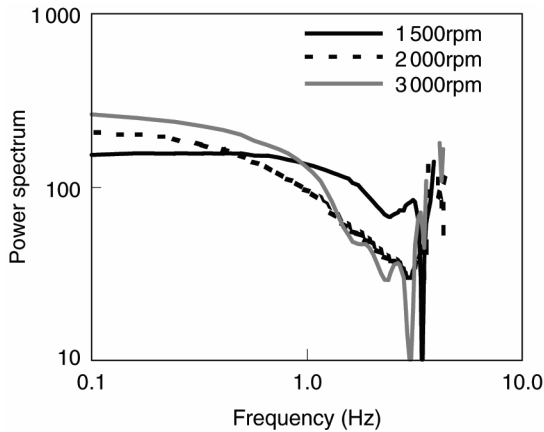


Fig. 5 Frequency characteristics under several engine speed conditions

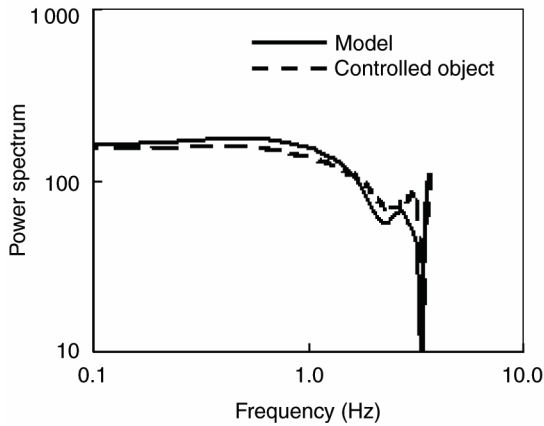


Fig. 6 Frequency characteristics comparison between model and controlled object at 1 500 rpm

Table 2 Model parameters of controlled object model at 1 500rpm

| $a_1$ | $a_2$ | $b_1$ | $b_2$  |
|-------|-------|-------|--------|
| 1.83  | -0.84 | 34.53 | -31.84 |

### 4.2. Adaptive Disturbance Observer

As  $N_{eh}$  is defined as the estimated value of  $N_e$  by Eq. (2), which was obtained by shifting Eq. (1) to the previous control time-step and adding  $c_1$ , the adaptive disturbance observer estimates  $c_1$  to minimize the difference between  $N_{eh}$  and  $N_e$ .

$$N_{eh}(k) = a_1 N_e(k-1) + a_2 N_e(k-2) + b_1 T_{hr}(k-1) + b_2 T_{hr}(k-2) + c_1(k-1) \quad (2)$$

$c_1$  : Estimated disturbance value

Here,  $c_1$  is estimated as shown in the equation below using the fixed gain method that is used by adaptive control<sup>(6)</sup>.

$$c_1(k) = c_1(k-1) + \frac{P}{1+P} e_{dov}(k) \quad (3)$$

$$e_{dov}(k) = N_e(k) - N_{eh}(k)$$

$P$ : Estimated gain

### 4.3. Sliding Mode Controller

When using an adaptive disturbance observer, the control input  $T_{hr}$  of the sliding-mode controller is calculated as the sum of the two inputs  $U_{eq}$  and  $U_{rch}$  as follows.

$$T_{hr}(k) = U_{eq}(k) + U_{rch}(k) \quad (4)$$

At this time, by defining  $\sigma$  and the error  $E_{ne}$  as shown in Eqs. (5) and (6),  $U_{rch}$  can be calculated using Eq. (7).

$$\sigma(k) = E_{ne}(k) + S E_{ne}(k-1) \quad (5)$$

$$E_{ne}(k) = N_e(k) - N_{er}(k) \quad (6)$$

$S$ : Switching function setting parameter

$$U_{rch}(k) = \frac{-K_{rch}}{b_1} \sigma(k) \quad (7)$$

$K_{rch}$ : Reaching law gain

In addition,  $U_{eq}$  is defined as the input that restricts the combination of the errors  $E_{ne}(k)$  and  $E_{ne}(k-1)$  (hereafter, the “state”) onto the line indicated by  $\sigma = 0$ , in other words, the switching line. Therefore,  $U_{eq}$  can be obtained as shown in Eq. (9) by substituting the left side of the conditional formula shown in Eq. (8) into Eq. (2) and solving for  $T_{hr}$ .

$$\sigma(k+1) = \sigma(k) \quad (8)$$

$$U_{eq}(k) = \frac{1}{b_1} \{ (1 - S - a_1)N_e(k) + (S - a_2)N_e(k-1) + N_{er}(k+1) + (S - 1)N_{er}(k) - SN_{er}(k-1) - b_2T_{hr}(k-1) \} - c_1(k) \quad (9)$$

Here, the  $U_{eq}$  obtained using Eq. (9) adds the final term  $c_1$  which serves to compensate for disturbance to the  $U_{eq}$  when also using  $U_{adp}$ , as shown in Fig. 3.

## 5. Simulation Results

A virtual engine was created by substituting the model parameters shown in Table 2 into the block diagram shown in Fig. 7 in order to simulate and compare the disturbance suppression performance of SMC using  $U_{adp}$  and SMC using an adaptive disturbance observer. Disturbance  $d_1$  which estimates the variation and aging-induced changes in the engine torque characteristics, and disturbance  $d_2$  which estimates the electrical load and other factors were applied to this virtual engine as shown in Fig. 8. In addition,  $N_{er}$  was set at 2 000 rpm in the simulation.

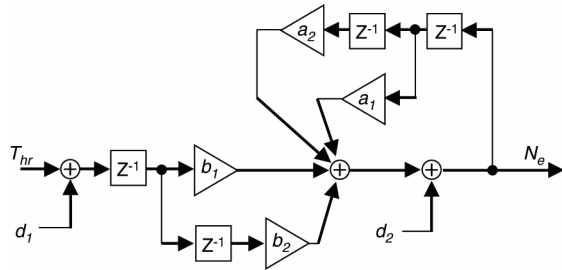


Fig. 7 Controlled object model for comparison between conventional and newly designed sliding-mode controller

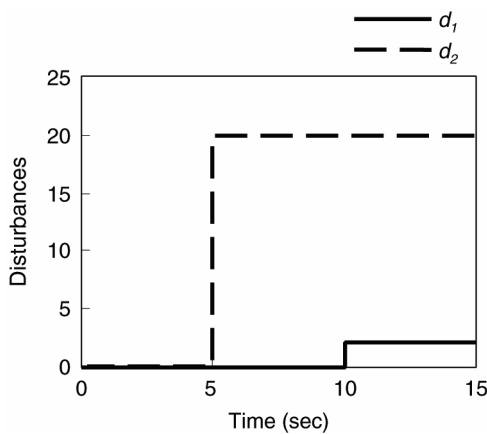


Fig. 8 Disturbances inputted to controlled object model

The simulation results showed that when  $U_{adp}$  was used, the integral characteristics of  $U_{adp}$  produced both oscillatory converging behavior and significant overshoot in response to both  $d_1$  and  $d_2$  as shown in Fig. 9.

On the other hand, when an adaptive disturbance observer was used, slight overshoot occurred in response to  $d_2$ , but the settling time after the disturbance was about half that when using  $U_{adp}$ , and there was also no oscillatory behavior, as shown in Fig. 10.

These results indicate that the SMC using an adaptive disturbance observer provides superior overshoot suppression capability and a faster response.

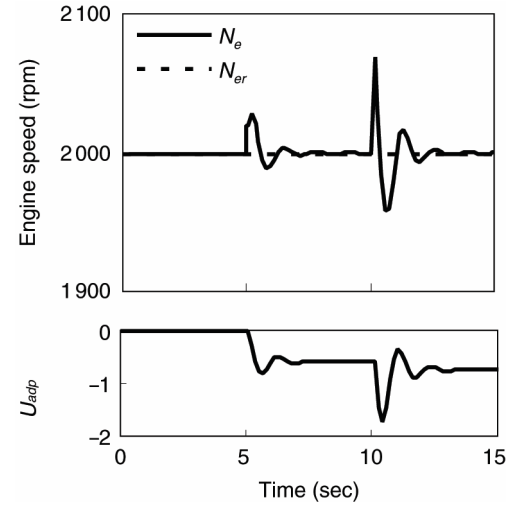


Fig. 9 Simulation results for sliding-mode controller with  $U_{adp}$

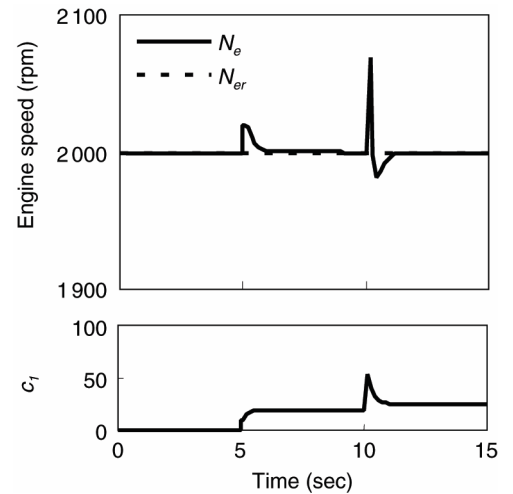


Fig. 10 Simulation results for sliding-mode controller with adaptive disturbance observer

## 6. Test Results

### 6.1. Comparison of Step Response

The step responses for PID control, SMC using the adaptive law input, and SMC using an adaptive disturbance observer were compared using the engine described in Table 1. Figure 11 shows the results.

These results show that the SMC using an adaptive disturbance observer provides superior overshoot suppression capability compared to the other controls that have integral elements.

### 6.2. Robustness against Engine Warm-up Conditions

Figure 12 compares the  $N_e$  step responses obtained by the SMC using an adaptive disturbance observer under the conditions before warm-up (immediately after engine startup), and after warm-up.

These results show that the SMC using an adaptive disturbance observer exhibits a stable target value tracking response regardless of the warm-up conditions.

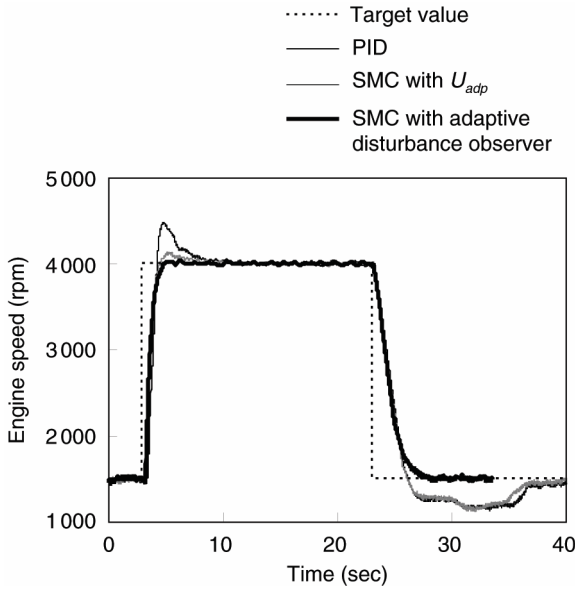


Fig. 11 Step responses controlled by PID, SMC, with  $U_{adp}$  and SMC with adaptive disturbance observer

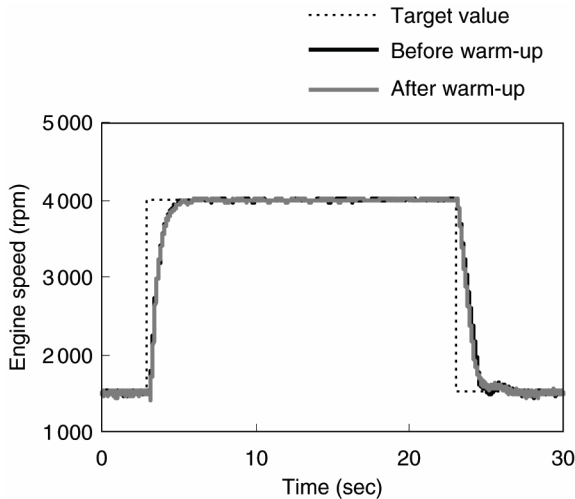


Fig. 12 Step responses before and after warm-up

### 6.3. Robustness against Engine Torque Characteristic Error

Figure 13 shows the control results when errors of +50%, 0%, and -50% are applied to the throttle angle in order to evaluate the robustness of the SMC using an adaptive disturbance observer against engine torque characteristic error. In addition, the control results for the SMC using  $U_{adp}$  with a throttle angle error of 0% are also shown.

Even when an error of -50% was applied, the SMC using an adaptive disturbance observer realized a settling time equivalent to that for the SMC using  $U_{adp}$  with 0% error, and also exhibited a smaller overshoot than the SMC using  $U_{adp}$  when an error of +50% was applied.

This confirms that the SMC using an adaptive disturbance observer has superior robustness.

## 7. Conclusion

Sliding mode control using an adaptive disturbance observer was applied to engine speed control, and the following results were obtained:

- (1) Overshoot was dramatically reduced compared to controls that have integral elements for compensating steady-state error.
- (2) Stable controllability was realized that is independent of the engine warm-up state.
- (3) Robustness against engine variation and aging-induced changes in the engine torque characteristics was dramatically enhanced.

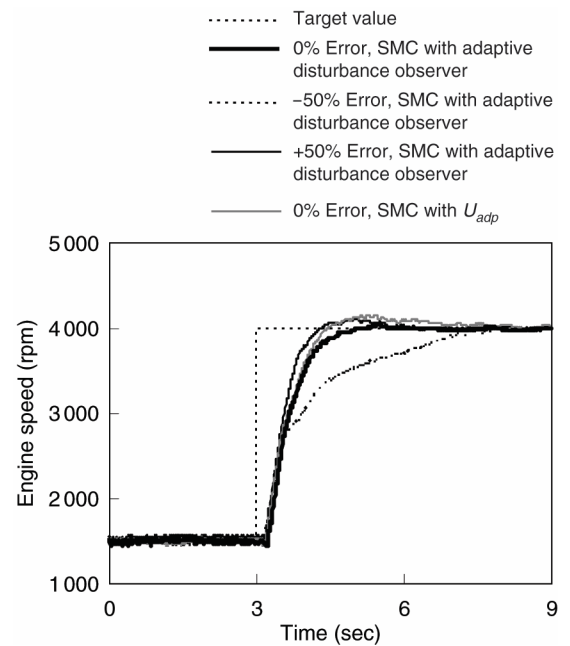


Fig. 13 Robustness against engine torque error

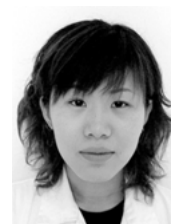
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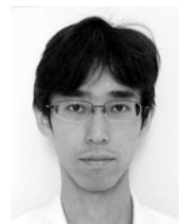
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