

Development of Electronic Throttle Control Utilizing Adaptive Control Method

Eiji HASHIMOTO*

Yuji YASUI*

Tetsuya ISHIGURO*

Shusuke AKAZAKI*

ABSTRACT

Electronic throttle control has been focused upon in recent years as a measure to provide greater accuracy for idling air control and to help reduce emissions. For this reason, it is necessary to achieve greater robustness in throttle control performance, to cope with variations between individual units and degradation of parts over time. Up to the present, it has been difficult for PID control systems to recognize unspecified disturbances, and this has been an impediment to achieving a balance between robustness and responsiveness. To perform robustness, an adaptive control system has been constructed which utilizes sliding mode control and contains an identifier to perform sequential calculations. This technology has realized previously unavailable levels of robustness, accuracy, and responsiveness in an electronic throttle control.

1. Introduction

Electronic throttle control has been used in recent years to coordinate vehicle traction control and automatic transmission to improve vehicle stability and ride comfort. However, environmental measures such as fuel economy and reduced emissions are also demanded, and electronic throttle control has come to be widely used in the control systems of new engines such as for direct injection engine vehicles, hybrid vehicles, low emission vehicles (LEV) and so on.⁽¹⁾

However, when electronic throttle control is closely and complexly intertwined with multiple other control systems, the dynamic characteristics fluctuate due to dynamic characteristic variance caused by variation in the throttle angle sensor, drive gear, drive DC motor and other components, changes in the operating environment such as temperature, and degradation over time, etc. This made it

difficult to maintain stable control system characteristics, so control system stability was ensured by reducing the control performance.

For example, when PID control is used as the throttle angle drive control, changes in the dynamic characteristics due to the throttle angle and disturbances can be coped with by scheduling the feedback gain according to the throttle angle. However, variation or changes in the dynamic characteristics due to variations in individual components or degradation over time is difficult to observe with PID control. This means that the feedback gain cannot be changed to an appropriate value, which led to a drop in tracking performance and stability with respect to the throttle angle target value. Application of adaptive control⁽²⁾ using an on-board identifier that successively estimates dynamic characteristic variation, fluctuation and disturbances was considered as a means for resolving these problems.

* Tochigi R&D Center

Therefore, this study applied a new adaptive control capable of adapting even to changes in the dynamic characteristics caused by rapid changes in the throttle angle to electronic throttle control, and realized both high robustness and excellent control performance. This paper reports these results.

2. System Concept

As shown in Fig. 1, this technology aims to create an electronic throttle control system that achieves a high degree of balance between performance, reliability and smartness.

In terms of performance, the system aims to realize a response and control resolution that can emphasize driving enjoyment and satisfy the required safety and environmental performances.

For reliability, the hardware was designed with durability equal to or greater than systems combining a mechanical throttle and idling air control valve. Also, using adaptive control for throttle angle control made it possible to compensate for variance and changes over time in each hardware property, and maintained control system stability even when the properties change such as when the hardware breaks down. This realized the same reliability as a mechanical throttle.

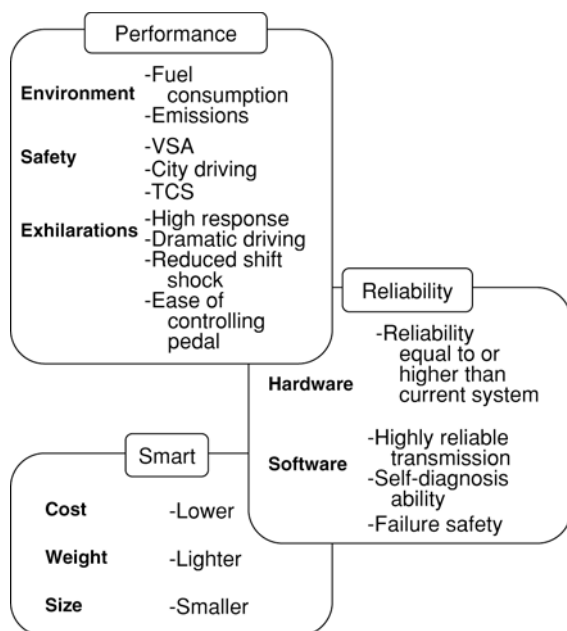


Fig. 1 Electronic throttle control system concept

In the area of smartness, the application of adaptive control improved response and reliability, which reduced the maximum motor torque and eliminated the clutch mechanism for separating the motor from the throttle in the event of a breakdown. This realized size, weight and cost reductions.

2.1. System Layout

Figure 2 shows the on-board layout of the throttle body, accelerator pedal and throttle driver for an engine that uses electronic throttle control.

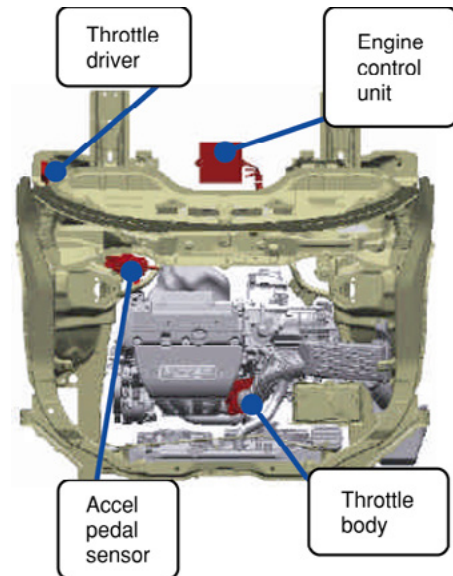


Fig. 2 Layout of electronic throttle control system

As shown in Fig. 3, this system is a dispersed function type architecture that connects the engine control unit and the electronic throttle control using a master-slave system. The electronic throttle control driver is separated from the engine control unit, so the system can be added to the engine control units of multiple models without altering the existing hardware.

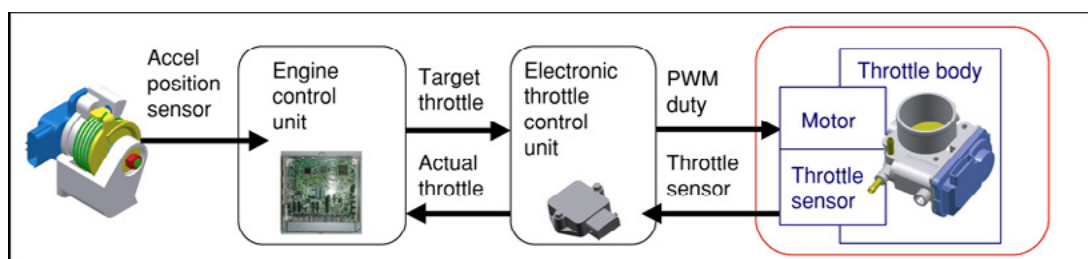


Fig. 3 Electronic throttle control system outline

2.2. Default Angle

The limp-home concept aims to allow a vehicle to move to a service center under its own power when a particular device breaks down, even if normal cruising is not possible.

In order to realize this concept with an electronic throttle control system, the throttle angle is maintained at a certain angle (hereafter “default angle”) by only the force of a spring when driving force is not generated on the engine as shown in Fig. 4. Therefore, the direction of the spring force applied to the throttle valve is inverted near the default angle as shown in Fig. 5. This causes the throttle angle to exhibit nonlinear behavior relative to the motor driving force, which results in lower control performance near the default angle.

3. Adaptive Control Algorithm

When the source voltage is low such as during engine startup or at low air temperatures, the motor drive control feedback gain must be increased at the throttle angle position where the spring tension is not constant near the default angle as shown in Fig. 4 and Fig. 5. However, if this setting is inappropriate, the throttle angle exhibits vibratory behavior.

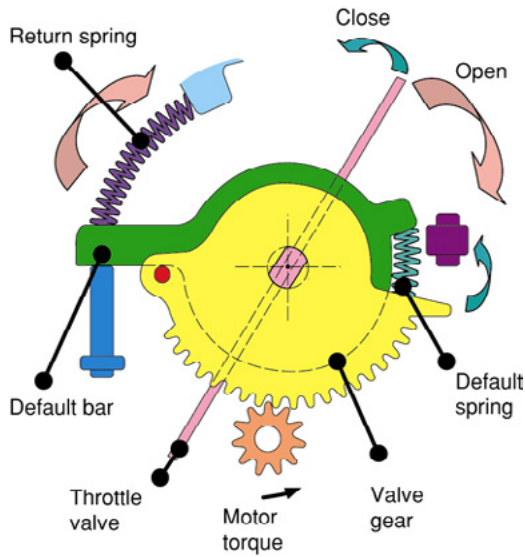


Fig. 4 Outline of default mechanism for electronic throttle

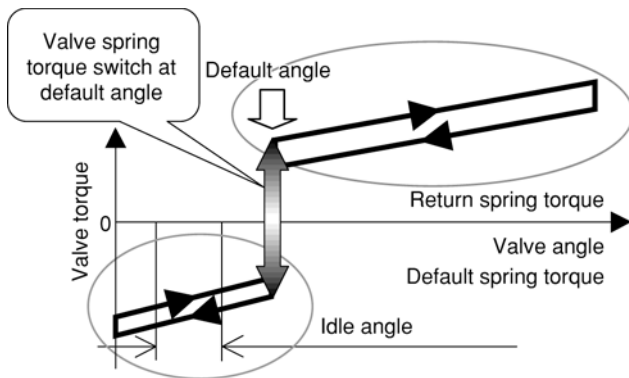


Fig. 5 Valve spring torque characteristic

Therefore, when performing motor drive control by PID control, the control performance must be suppressed to ensure stability by presetting a low feedback gain.

In addition, engine oil, suspended carbon, EGR and other various foreign substances pass through the vehicle throttle, and these foreign substances adhere to the shaft, bearing and valve and cause component wear. This means that changes in friction occur which are difficult to predict, that is to say changes in the dynamic characteristics occur.

However, PID control cannot preset the feedback gain for these immeasurable changes in dynamic characteristics, so the control performance deteriorates even further.⁽³⁾ PID control with a disturbance observer⁽⁴⁾ and I-PD control systems⁽⁵⁾ have been constructed as means to deal with this issue, but these systems also suffer drops in control performance when the dynamic characteristics change significantly.

Therefore, this study constructed a new adaptive control and applied it to the motor drive control. This new adaptive control combines a model parameter scheduler that compensates for rapid changes in the dynamic characteristics according to the throttle angle, an on-board identifier for adapting to variation and changes over time in the dynamic characteristics, and a sliding mode controller that realizes rapid response to the throttle angle target value and excellent control performance near the default angle. (Fig. 6) This system successively identifies the optimum control parameters and calculates the proper feedback gain based on these parameters. Therefore, stability with respect to changes in the dynamic characteristics can be ensured while maintaining excellent electronic throttle control performance even when the dynamic characteristics change in a manner that would reduce the control performance of PID control equipped with a disturbance observer, etc. This control algorithm is described in detail below.

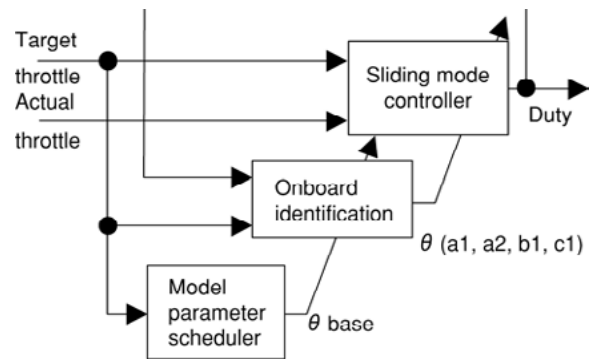


Fig. 6 Block diagram of electronic throttle control

3.1. Modeling

The electronic throttle control dynamic characteristics, fluctuations, and disturbance information related to these dynamic characteristics are converted to numeric form and used to calculate the feedback gain of the controller. Therefore, electronic throttle control was modeled using the ARX model (auto-regressive exogenous model) shown by

Eqs. (1) and (2). In this model, $a1$ and $a2$ which are related to the control subject output DTH, $b1$ which is related to the input DTH, and $c1$ which reflects disturbance and modeling error are set as the model parameters. These model parameters are calculated successively by the on-board identifier described hereafter.

$$DTH(n+1)=a1' DTH(n)+a2' DTH(n-1) +b1' DUT(n-d)* Vbat+c1' \quad (1)$$

$$DTH(n)=TH(n) - TH_DEF \quad (2)$$

DTH(n) : Deviation between throttle angle and default position
 TH(n) : Throttle angle
 TH_DEF : Throttle default angle
 DUT : PWM drive duty
 Vbat : Source voltage
 d : Wasted time
 $a1', a2', b1', c1'$: Model parameters

Figure 7 compares the frequency responses for this model and the control subject of the electronic throttle control. This figure shows that the model closely expresses the frequency response of the control subject. This indicates that the appropriate control input can be determined according to changes in the dynamic characteristics of the control subject and disturbances by successively calculating the feedback gain based on the model parameters of this model.

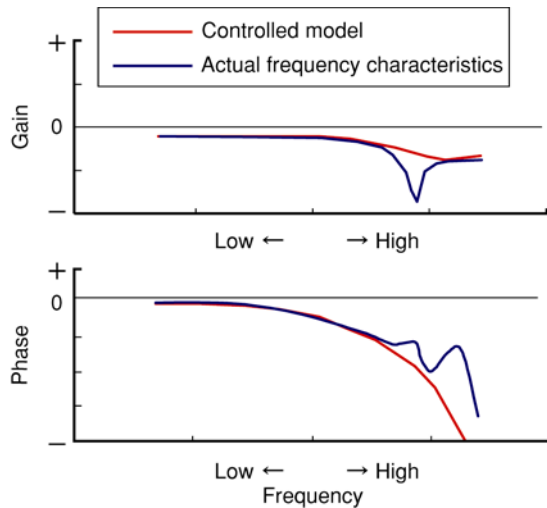


Fig. 7 Frequency characteristics

3.2. On-board Identifier

The on-board identifier identifies the above model parameters using the identification algorithm indicated in Eqs. (3) to (7). This algorithm calculates the model parameters by adding the model parameter update

components calculated based on the error eid between the model output DTHHAT and the control subject output DTH to the reference model parameters calculated by the parameter scheduler described hereafter. At this time the reference model parameters are set according to the throttle opening which has a correlation with the changes in the dynamic characteristics of the control subject. This solved the issue of the delay in model parameter identification⁽³⁾ when the dynamic characteristics of the control subject change rapidly for general adaptive control, that is to say when the throttle angle changes rapidly.

Furthermore, parameter $c1$ is the model parameter signifying nonlinear control subject characteristics and disturbance, and this absorbs constant disturbance and steady-state error. This ensures high robustness with respect to changes in the dynamic characteristics of the control subject due to source voltage fluctuations and deterioration over time, etc.

$$DTHHAT(n+1)=a1 DTH(n)+a2 DTH(n-1)+b1 DUT(n-d)*Vbat+c1 \quad (3)$$

$$\theta(n) = \theta base(n)+d\theta(n) \quad (4)$$

$$d\theta(n) = d\theta(n) + KQ(n)*eid(n) \quad (5)$$

$$eid(n) = DTH(n) - DTHHAT(n) \quad (6)$$

$$KQ(n) = P\zeta(n)/1 + \zeta^T(n) P\zeta(n) \quad (7)$$

θ base: Model parameter reference value determined by the model parameter scheduler according to the throttle angle
 $\zeta(k)$: $[DTH(n-1) DTH(n-2) DUT(n-1) 1]^T$
 $a1, a2, b1, c1$: Model parameter identification values

3.3. Model Parameter Scheduler

The model parameter scheduler calculates the reference model parameters $a1base$, $a2base$ and $b1base$ according to the control subject output DTH. These reference model parameters are set as the values of model parameters $a1$, $a2$ and $b1$ which represent the dynamic characteristics of the electronic throttle control near each DTH. Therefore, when variation or change over time occurs in the dynamic characteristics of the electronic throttle control, the on-board identifier corrects only the error between the reference model parameters and the model parameters which is produced by changes in the dynamic characteristics. This makes it possible to reduce the parameter correction amount at each DTH, which minimizes the model parameter identification delay.

3.4. Scheduling Mode Controller

The sliding mode controller⁽⁶⁾ calculates the input DUT to the control subject using the model parameters identified by the on-board identifier. Labeling the control time of the controller as n , the proportional function $\sigma(n) = 0$ called the switching line is defined on the phase plane having as axes the current value $e(n)$ and previous value $e(n-1)$ of the deviation between the throttle angle target value and the actual angle as shown in Fig. 8. At this time the sliding mode controller performs control to keep the combination of $e(n)$ and $e(n-1)$ (hereafter "status level") to the switching line, and this status level is then converged toward the origin of the phase plane unaffected by disturbances or control subject modeling error. Also, the control input DUT is calculated as the sum of the three inputs shown below.

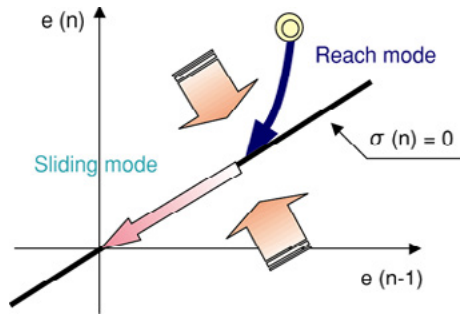


Fig. 8 Sliding mode control outline

Equivalent control input $U_{eq}(n)$: Input to keep the status level on the switching line

Reach input $U_{rch}(n)$: Input to converge the status level onto the switching line

Damping input $U_{dmp}(n)$: Input to prevent overshoot of the throttle angle target value

The combination of model parameter operations by the on-board identifier described above and this sliding mode realized rapid response, high control precision, and robustness with respect to modeling error, gear backlash and source voltage fluctuation.

4. Test Results Using a Discrete Unit Tester

4.1. Response Variation during Source Voltage Fluctuation

Figure 9 shows the results of comparing the variation in the response time with PID control at stepped target throttle values under conditions of a source voltage from 10.5 V to 16 V which is the normal control range for electronic throttle control.

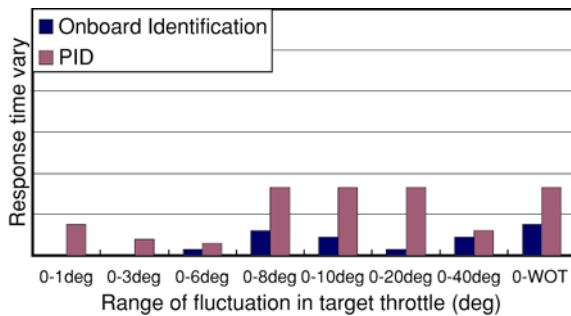


Fig. 9 PID and onboard identification method response time Max – Min varies between 10.5 V – 16 V input voltages.

This figure shows that the variation in the response time when using adaptive control is smaller than that for PID control at all target value fluctuation amounts. This confirmed the control performance stability relative to source voltage fluctuations caused by changes in the air temperature or battery deterioration, etc.

4.2. Response during Voltage Fluctuation

Figure 10 shows the results of comparing the response time with PID control for stepped target throttle values. This figure shows that the response time for adaptive control is shorter than for PID control which reduces the feedback gain due to concerns of producing vibratory behavior.

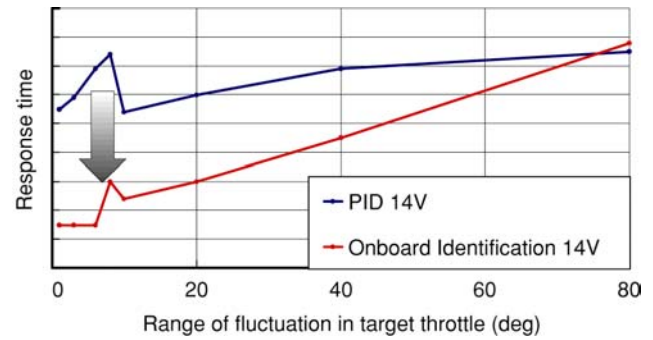


Fig. 10 Difference in response time for PID and onboard identification method.

4.3. Response Changes due to Variation in the Physical elements of the Throttle Drive System

Figure 11 and Fig. 12 show the response time variation and the response waveform relative to the stepped target values when using four types of electronic throttle control with different throttle body characteristics. These figures show that even when the friction fluctuates, the adaptive control response time and fluctuation amount are less than for PID control, and the response behavior is also smaller.

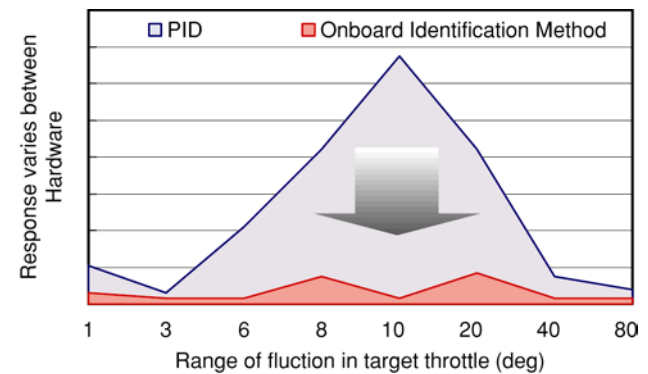


Fig. 11 Difference in response time for PID and onboard identification system with different throttle body characteristics.

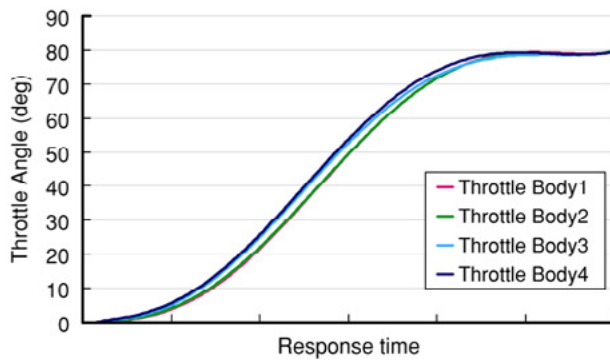


Fig. 12 Response chart graph of different throttle body characteristics.

- (4) Kunifuda, Nakamura, Matsuyama: Development of a Robust Electronic Throttle Control System, Automotive Technology, Vol. 52, No. 9, pp. 37-42 (1998)
- (5) Oguni, Mita: Introduction to System Control Theory, Tokyo, Jikkyo Publishing, pp. 121-132 (1979)
- (6) Nonami, Den: Sliding Mode Technology, Tokyo, Corona Publishing, pp. 41-54 (1994)

5. Actual Vehicle Test Results

Running tests were conducted using test vehicles on a test course under hypothetical conditions of cruising at high speed, low speed, normal speed, and congested roads. During these tests the throttle angle was confirmed to be within ± 0.2 degrees of the target angle 80% or more of the time, indicating that the system has sufficient performance as a vehicle control device. In addition, idling control performance was equal to or better than the engine speed control performance using a conventional air idling control valve device.

6. Conclusions

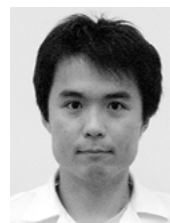
The following effects were obtained by applying adaptive control comprised of an on-board identifier, parameter scheduler and sliding mode controller to an electronic throttle control system.

- (1) Rapid response and robustness were simultaneously achieved, which was difficult for PID control.
- (2) Stable control performance was ensured not only with respect to changes in the environment, deterioration over time and parts variance, but also with respect to source voltage fluctuation and other disturbances.
- (3) The results of tests using actual vehicles confirmed that the throttle angle was within ± 0.2 degrees of the target angle 80% or more of the time during idling control and throttle control while cruising.

References

- (1) McKay, D., et. al.: Delphi Electronic Throttle Control Systems for Model Year 2000; Driver Features, System Security, and OEM Benefits. ETC for the Mass Market, SAE 2000-01-0556 (2000)
- (2) Yasui, A., Ueno, I.: Adaptive Sliding Mode Control for Secondary O_2 Feedback (Part 3), Honda R&D Technical Review Vol. 13, No. 2, pp. 59-66 (2001)
- (3) Terao, K.: Introduction to Robust Adaptive Control, Tokyo, Ohm Publishing, pp. 9-11 (1989)

■ Authors ■



Eiji HASHIMOTO



Tetsuya ISHIGURO



Yuji YASUI



Shusuke AKAZAKI