

Adaptive Sliding Mode Control for Secondary O₂ Feedback (Third Report)

—Improvement of Adaptability by Using Prediction and Identification Sliding Mode Control—

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ABSTRACT

Secondary O₂ feedback is one effective method for reducing vehicle emissions, and the improvement of this performance yields even greater emissions reductions. This report details a significant advance in the algorithm for the sliding mode controls that were described in our first and second reports, and the application of this newly designed algorithm to secondary O₂ feedback. The results show that feedback control performance was significantly improved under all engine loads and catalyst aging conditions. Moreover, the FTP mode emissions were reduced by 32 - 42%, and the emissions stability with respect to catalyst aging conditions was dramatically improved.

1. Introduction

The first⁽¹⁾ and second⁽²⁾ reports explained secondary O₂ feedback^{(1) - (5)} methods improved by modeling an exhaust system including a catalyst by the use of an auto-regressive exogenous model⁽⁶⁾ and by applying an adaptive sliding mode control^{(1), (7)} and prediction sliding mode control⁽²⁾ which have high robust stability. However, the difficulties in improving the performance of secondary O₂ feedback remained. These include:

- (1) Stability improvements relative to the nonlinear dynamic characteristic of the catalyst
- (2) Stability improvements relative to the dead time characteristic of the catalyst
- (3) Adaptability relative to changes in catalyst response characteristics due to catalyst aging conditions and engine load conditions.

However, the previous algorithm did not have sufficient stability with respect to item (3).

Therefore, a prediction and identification sliding mode control^{(8), (9)} was designed by the addition of an identifier to the prediction sliding mode control explained in the second report. The identifier successively calculates (identifies) the parameters of the exhaust system model and resolves the outstanding difficulty outlined above.

This report describes the design method for the improved control algorithm and its effect on control performance and reducing emissions.

2. Background and Approach

2.1 Focus on Reducing Emissions

Fig. 1 shows the layout of the catalyst and sensors generally used in engines adopting secondary O₂ feedback. In this example, a linear air-fuel ratio sensor is positioned upstream of the catalyst (the diagram's Universal Air-Fuel Ratio Heated Exhaust Gas Oxygen sensor: UEGO sensor),

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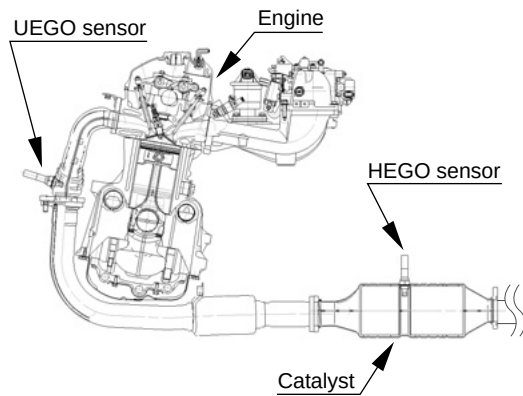


Fig. 1 Layout of sensors and the three-way catalyst

and a secondary O_2 sensor downstream (the diagram's Heated Exhaust Gas Oxygen sensor: HEGO sensor).

In the engine in the figure, the output of the linear air-fuel ratio sensor, according to the air-fuel ratio in the air-fuel mixture, is defined as ϕ_{in} . The output voltage of the secondary O_2 sensor, according to the exhaust gas composition after the catalyst, is defined as V_{out} . Furthermore, the CO, HC, and NOx concentrations upstream and downstream of the catalyst according to the engine operating air-fuel ratio were acquired by an exhaust gas analysis device; the catalyst conversion rates at each exhaust gas volume condition were calculated on the basis of those concentrations as shown in Fig.2. Fig.2 shows the relation between V_{out} and the exhaust gas volume when the catalyst conversion rates for the CO, HC, and NOx are each 90% or more. In the graph, when V_{out} indicates the optimum value around 0.6V (referred to as V_{op} hereafter), the catalyst conversion rate is optimized regardless of the exhaust gas volume conditions. However, this trend at exhaust gas volumes below 2000L/h is obscure due to the insufficient precision of the exhaust gas analysis device.

Therefore, regardless of the engine load conditions or

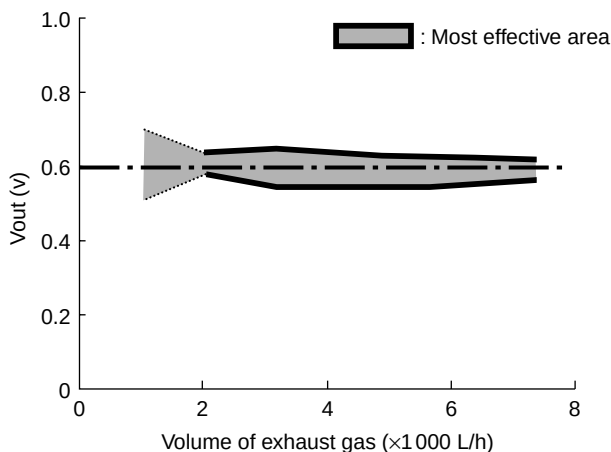


Fig. 2 Relation between the most effective catalyst conversion rate range and exhaust gas volume

the catalyst aging conditions, constantly controlling V_{out} to the fixed target V_{op} is the best way to optimize the catalyst conversion rate of the engine-exhaust system used in this system. In this report, controlling V_{out} at V_{op} is achieved by improving the controllability of the secondary O_2 feedback.

2.2 Technical Issues Related to Secondary O_2

Feedback

As mentioned previously, in order to improve the controllability of the secondary O_2 feedback, it is necessary to improve the stability of the following catalyst characteristics.

- 1) Non-linear dynamic characteristics
- 2) Dead time characteristics
- 3) Change in dynamic characteristics due to engine load conditions and catalyst aging conditions.

Each of these will be discussed in detail below.

2.2.1 Non-linear dynamic characteristics of the catalyst

Fig. 3 shows the ϕ_{in} and V_{out} data when ϕ_{in} is oscillated in a sine wave pattern with a frequency of 0.2Hz and an amplitude of 0.2A/F under catalyst aging condition equivalent to 50,000 miles and under 50mph cruise condition. In the graph, the response of V_{out} according to the ϕ_{in} change from lean to rich is different from that of from rich to lean. This is the non-linear dynamic characteristic of the catalyst caused by the chemical reaction change of the catalyst according to the direction of ϕ_{in} change.

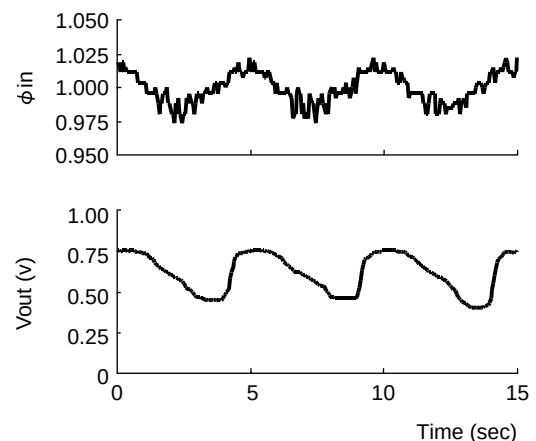


Fig. 3 Nonlinear characteristics of a catalyst

2.2.2 Dead time characteristics of the catalyst

Fig. 4 shows the ϕ_{in} and V_{out} data when ϕ_{in} is changed in a step pattern under catalyst aging condition equivalent to 120,000 miles. In the graph, corresponding to the ϕ_{in} lean to rich reversal, the V_{out} reversal has an ineffective period. This is the dead time characteristic of the catalyst, which mainly occurs due to the oxygen absorbing and storing characteristic of the catalyst.

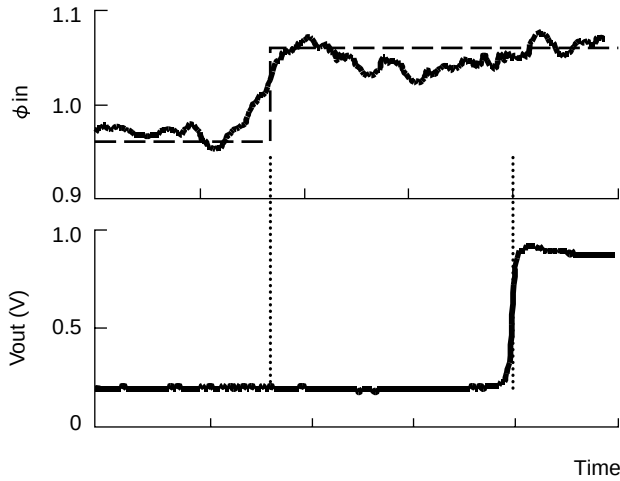


Fig. 4 Dead time characteristics of a catalyst

2.2.3 Changes in the dynamic characteristics of the catalyst

Fig. 5 shows the power spectra from the Fourier transformation of the V_{out} measured when using catalysts aged to the equivalents of 50,000 miles and 200,000 miles under 50 mph cruise conditions. In the graph, as the deterioration proceeds, power spectra at each frequency increases. Furthermore, the trend rises, as the frequency becomes higher. This shows that the dynamic characteristics of the catalyst change according to catalyst aging conditions.

In addition, when engine load conditions change, the same dynamic characteristics change can be seen. In this case, when engine load conditions change to the high load direction, catalyst dynamic characteristics change in the same direction that they do in the catalyst aging process.

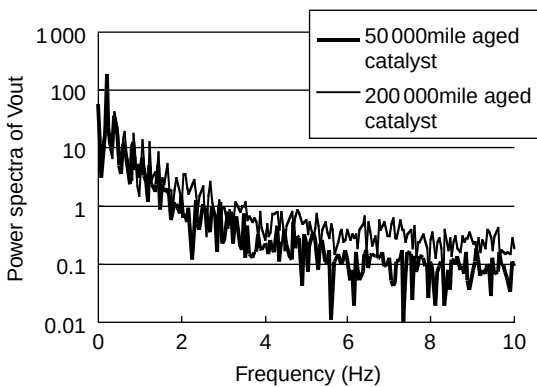


Fig. 5 Frequency characteristics of catalysts

2.3 Resolution Methods

In order to improve the stability of secondary O₂ feedback with respect to the three catalyst characteristics stated above, and to maximize the catalyst conversion rate, a new control algorithm, the Prediction and Identification Sliding Mode control (referred to as PRISM hereafter) was designed. As shown in Fig. 6, PRISM is composed of the following three elements.

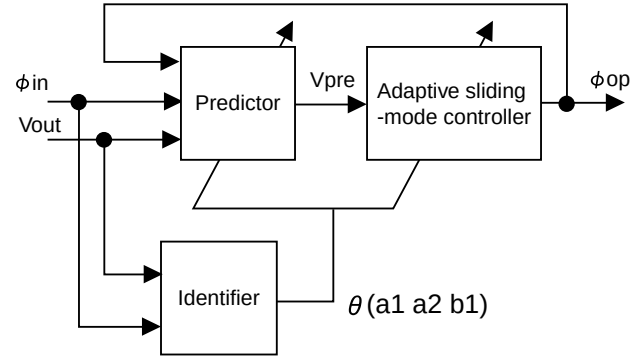


Fig. 6 Prediction and identification sliding mode control (PRISM)

- 1) An adaptive sliding-mode controller
- 2) A predictor
- 3) An identifier

The identifier determines model parameter θ (a_1 , a_2 , b_1) of the exhaust system model explained below on the basis of the changes in catalyst dynamic characteristics. This adapts the sliding-mode controller and the predictor to those changes.

The predictor calculates V_{pre} , which is the prediction value of V_{out} , on the basis of θ , V_{out} , ϕ_{in} , and the target value for ϕ_{in} (referred to as ϕ_{op} hereafter) in order to compensate for the dead time characteristics of the catalyst.

The sliding-mode controller compensates for the modeling error in the exhaust system model described below and for the non-linear dynamic characteristics of the catalyst by using its robustness. Furthermore, it calculates ϕ_{op} in order to control V_{out} to V_{op} on the basis of θ and V_{pre} .

Consequently, PRISM resolves the three aforementioned issues by combining three elements, and it provides an accurate convergence of V_{out} to V_{op} .

Furthermore, Fig. 7 is a block diagram of the total fuel control system using PRISM. In the system, ϕ_{op} is calculated by PRISM and STR (Self-tuning Regulator)⁽¹⁰⁾ is applied to the air-fuel ratio control upstream of the

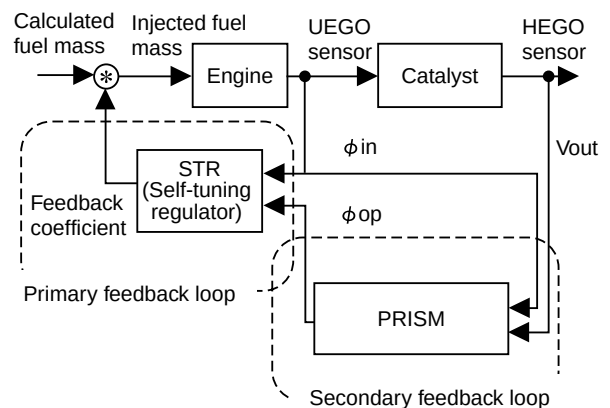


Fig. 7 Overall configuration of the double feedback loop

catalyst in order to control ϕ_{in} to ϕ_{op} . As a result, this double feedback loop composed of PRISM and STR achieves V_{out} convergence on converged V_{op} .

Details are provided below.

3. Modeling

In the air-fuel ratio control system shown in Fig. 7, the combination of STR, the engine, and the exhaust system up to the linear air-fuel ratio sensor is defined as the engine system, and the exhaust system, including the catalyst, from the linear air-fuel ratio sensor to the secondary O_2 sensor as the controlled object. Modeling for each of these systems is described below.

3.1 Engine System Modeling

The control system shown in Fig. 7 controls V_{out} by operating ϕ_{in} . Therefore, it is necessary to have ϕ_{in} follow ϕ_{op} in a highly accurate manner. However, the fuel transportation dynamics and combustion cycle of the engine cause dead time and lag characteristics between ϕ_{op} and ϕ_{in} . Therefore, it is necessary to compensate for these dynamic characteristics. However, as stated previously, the air-fuel ratio control system composed of PRISM and STR has a double feedback loop structure. Consequently, these two feedback loops overlap at the engine system, and cause interference.

Fig. 8 shows the ϕ_{in} response wave, when controlled by STR, for the rectangular wave ϕ_{op} . As can be seen from the graph, ϕ_{in} is the ϕ_{op} waveform shifted roughly with the de . This means that the lag characteristic of the engine system is sufficiently compensated for by STR. Therefore, the engine system can be thought to be a dead time element.

Consequently, in order to prevent interference of the double feedback loop, focus was placed on the relationship between ϕ_{in} and ϕ_{op} . As shown in Fig. 7, STR only compensates for engine system delay characteristics. Therefore, if PRISM does not carry out compensation for the lag characteristic of the engine system, the interference of the double feedback loops is prevented. Accordingly, in order to prevent interference, the roles of STR and PRISM are divided as follows. STR compensates for the lag characteristic of the engine system; and PRISM assumes that the engine system is the generator of ϕ_{in} , not one of

its controlled objects, and it considers only the dead time characteristics of the engine system when controlling V_{op} .

Here, because the engine system does not have a lag characteristic, it is modeled as a dead time element as shown below.

$$\phi_{in}(k) = \phi_{op}(k-de) \quad (1)$$

k : control time

de : engine system dead time

3.2 Exhaust System Modeling

The exhaust system including the catalyst, which is the controlled object for PRISM, as shown in Fig. 4 and Fig. 5, has low pass characteristics. That is to say, it has a lag characteristic and a dead time characteristic.

Considering this and the ease of on-board identification of model parameters by the identifier, a controlled object model was created using a DARX model (Delayed Auto-regressive eXogeneous model, an auto-regressive model that has dead time in the input).

$$VO2(k+1) = a_1 VO2(k) + a_2 VO2(k-1) + b_1 KACT(k-d) \quad (2)$$

$$VO2(k) = V_{out}(k) - VO2_TARGET \quad (3)$$

$$KACT(k) = \phi_{in}(k) - KACT_BASE \quad (4)$$

a_1, a_2, b_1	: Model parameters
$VO2(k)$	: Deviation between V_{out} and V_{op}
$VO2_TARGET$	: Target value V_{op}
$KACT(k)$	: Deviation between ϕ_{in} and $KACT_BASE$
$KACT_BASE$	: Standard value for ϕ_{in}
d	: Dead time of the exhaust system

4. Control Algorithm

The equations for the identifier, the predictor, and the adaptive sliding-mode controller, which comprise PRISM, are described below.

4.1 Identifier

The Weighted Recursive Least Squares method (WRLS hereafter) is generally known as an identification algorithm for the model parameters in the DARX model given in Equation (2).

This algorithm can successively renew model parameters according to the change in dynamics of a controlled object. Therefore, it is useful for adaptive controls.

However, Fig. 9 shows the identification weight at each frequency of the identification algorithm. Here, it can be seen that when the model parameters of the controlled object having low pass characteristics, as shown in Fig. 5, are identified by the identifier, the higher the frequency, the higher the identification weight as shown by the broken line in the graph. That is to say, the gain characteristics of the controlled object at high frequencies are stressed, when the

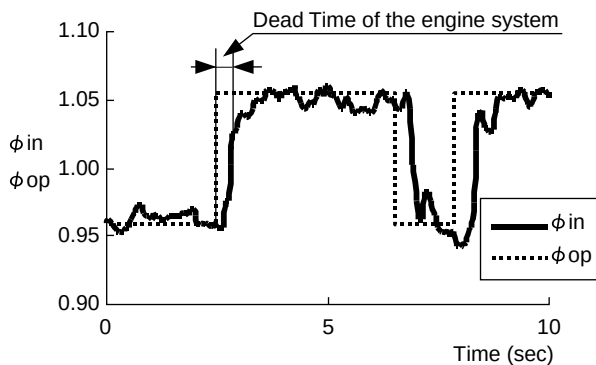


Fig. 8 Time series data of ϕ_{in} controlled by STR

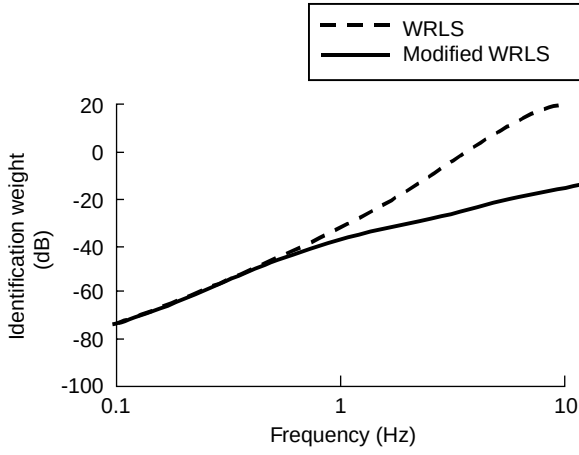


Fig. 9 Identification weight characteristics of basic and modified WRLS algorithms

controlled object model is identified⁽¹¹⁾. Fig. 10 shows the gain characteristics of the controlled object and the model. In the graph, the gain of the model identified by WRLS is smaller than the actual object. This is because the identification weight of WRLS emphasizes the cut-off characteristics of the controlled object at high frequencies. Such gain characteristics of the model make the compensation by the adaptive sliding-mode controller larger than needed, and deteriorates Vout controllability.

Therefore, in order to improve the identification weight of WRLS, the identification algorithm was modified, as shown in Equations (5) – (12).

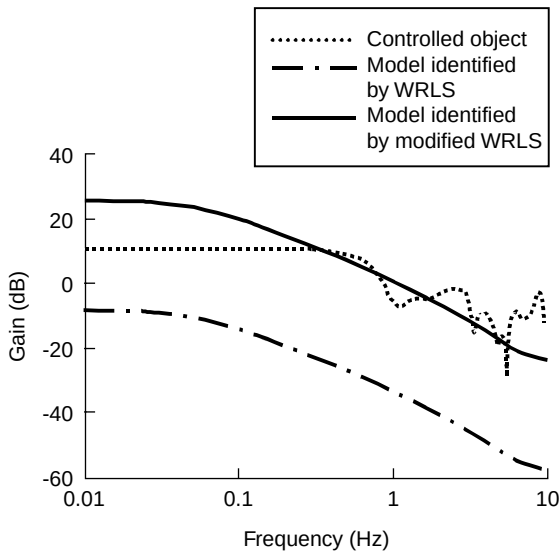


Fig. 10 Frequency characteristics comparison between the controlled and identified models

$$\theta(k+1) = \theta(k) + KP(k) e_{id_f}(k) \quad (5)$$

$$e_{id_f}(k) = \text{Fid}(e_{id}(k)) \quad (6)$$

$$e_{id}(k) = VO2(k) - VO2_hat(k) \quad (7)$$

$$VO2_hat(k) = \theta(k)^T \zeta(k-1) \quad (8)$$

$$KP(k) = \frac{P(k)\zeta(k-1)}{1 + \zeta^T(k-1)P(k)\zeta(k-1)} \quad (9)$$

$$P(k+1) = \frac{1}{\lambda} \left(I - \frac{P(k)\zeta(k-1)\zeta^T(k-1)}{\lambda + \zeta^T(k-1)P(k)\zeta(k-1)} \right) P(k) \quad (10)$$

$$\theta^T = [a_1 \ a_2 \ b_1] \quad (11)$$

$$\zeta^T(k) = [VO2(k) \ VO2(k-1) \ KACT(k-d)] \quad (12)$$

Fid() : low pass filter
 I : unit matrix
 λ : Weighting parameter ($0 < \lambda < 1$)

In the above algorithm, Equation (5) calculating θ is altered by replacing the identification error e_{id} used by conventional WRLS with the low pass filtered e_{id} (e_{id_f} hereafter). This improves the identification weight as shown by the solid line in Fig. 9. The identification weight at high frequencies according to the above algorithm is lower than by conventional WRLS. Further, the gain characteristics of the model identified by the modified WRLS are improved by correcting the identification weight with the low pass filter Fid, as illustrated with the solid line in Fig. 10. Accordingly, the above-mentioned over-compensation by the controller is suppressed.

4.2 Predictor

In order to explain the prediction algorithm, the deviation value of ϕ_{op} from the standard value KACT_BASE for ϕ_{in} is defined.

$$KCMD(k) = \phi_{op}(k) - KACT_BASE \quad (13)$$

KCMD(k): Deviation between ϕ_{op} and the standard value

Here, the engine system model expressed by Equation (1) becomes the equation below.

$$KACT(k) = KCMD(k-d_e) \quad (14)$$

In Section 3 it was explained that the engine system had lag and dead time characteristics, and that STR compensates for lag characteristics and PRISM assumes the system to be a dead time element in order to prevent interference between STR and PRISM.

The engine system is not the controlled object for PRISM, but rather it is an exhaust gas generator, which creates ϕ_{in} . That is to say, giving the example of a manipulator control, the engine system is equivalent to an actuator of a manipulator. However, because the engine system has dead time d_e , dead time exists until ϕ_{op} is reflected to ϕ_{in} . Therefore, this dead time deteriorates the stability and control performance of PRISM.

Accordingly, a total dead time dt is defined by PRISM by adding the dead time of the engine system, de , to the dead time of the controlled object d , as shown below.

$$dt = d + de \quad (15)$$

Moreover, PRISM compensates for d by predicting VO2.

In order to accomplish this, a prediction algorithm⁽¹³⁾ is applied. That is, the algorithm described by the equation below is used to calculate the prediction value VO2p(k) for VO2(k+dt).

$$VO2p(k) = \alpha_1 VO2(k) + \alpha_2 VO2(k-1) + \sum_{i=1}^{dt} \beta_i KACT(k+de-i) \quad (16)$$

$$Vpre(k) = VO2p(k) + Vop \quad (17)$$

$$A = \begin{bmatrix} a1(k) & a2(k) \\ 1 & 0 \end{bmatrix} \quad (18)$$

$$B = \begin{bmatrix} b1(k) \\ 1 \end{bmatrix} \quad (19)$$

α_1 : A^{dt} first row, first column element
 α_2 : A^{dt} first row, second column element
 β_j : A^{dt-1}B first row element

However, because Equation (16) uses the unknown future values of KACT, $KACT(k+de-1) \sim KACT(k+1)$, meaning ϕ_{in} , this equation is not possible to execute.

Thus, focusing on Equation (14), KCMD can be used as a substitute for the future values of KACT because STR sufficiently controls ϕ_{in} to ϕ_{op} .

$$KACT(k+de-1) \cong KCMD(k-1) \quad (20)$$

Accordingly, the executable algorithm using KCMD is created as below.

$$VO2p(k) = \alpha_1 VO2(k) + \alpha_2 VO2(k-1) + \sum_{i=1}^{de-1} \beta_i KCMD(k-i) + \sum_{j=de}^{dt} \beta_j KACT(k+de-j) \quad (21)$$

4.3 Adaptive Sliding-Mode Controller

As stated above, the predictor compensates for dead time dt by calculating VO2p, and the identifier compensates for the dynamic characteristic change of the controlled object by identifying model parameters a_1 , a_2 and b_1 . Therefore, in order to achieve superior control performance for VO2 while maintaining stability with respect to dead time and the dynamic characteristic changes of the controlled object, the adaptive sliding-mode controller

should determine ϕ_{op} on the basis of VO2p and identified model parameters.

Accordingly, the adaptive sliding-mode controller should determine ϕ_{op} to meet the equation below.

$$Vop = Vpre(k) \cong VO2''(k+dt) \quad (22)$$

In other words, the control subject of the controller is as follows.

$$VO2p(k) = 0 \quad (23)$$

At this time, the switching function σ to achieve Equation (23) is as follows.

$$\sigma(k) = VO2p(k) + S VO2p(k-1) \quad (24)$$

S: Switching function parameter

The equations for calculating ϕ_{op} on the basis of the switching function σ are as follows.

$$\phi_{op} = Ueq(k) + Urch(k) + Uadp(k) + KACT_BASE \quad (25)$$

$$Ueq(k) = \frac{-1}{b_1} \{(a_1-1) + S\} VO2p(k) + (a_2-S) VO2p(k-1) \quad (26)$$

$$Urch(k) = \frac{-1}{b_1} F \sigma(k) \quad (27)$$

$$Uadp(k) = \frac{-1}{b_1} G \sum_{i=0}^k \sigma(i) \quad (28)$$

5. Test Results

5.1 Verification of Controllability

5.1.1 Verification of robustness with respect to engine load conditions

In order to evaluate control stability with respect to engine load conditions, Vout data controlled by a conventional control method and by PRISM in the FTP mode is acquired using a prototype vehicle with L4 2.3 L engine and a catalyst (600 cell/4.3 mil) aged to an equivalent of 50,000 miles. The data results are then compared.

Fig. 11 and Fig. 12 show histograms of Vout controlled by PRISM and a conventional control method. As shown in these graphs, the Vout probability by the conventional method in the Vop range of $\pm 0.1V$ is 35.8%, and 74.3% by PRISM. Therefore it can be said that PRISM can double Vout controllability compared to the conventional method.

Fig. 13 shows the identified model parameters for the FTP mode. In the graph, model parameters change according to vehicle speed conditions – that is to say, according to engine load conditions. This reveals that the identifier continually adapts PRISM to the dynamic characteristic change of the controlled object according to engine load conditions.

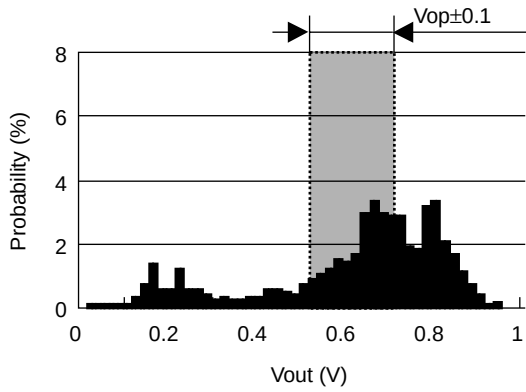


Fig. 11 Histogram of Vout controlled by conventional algorithm

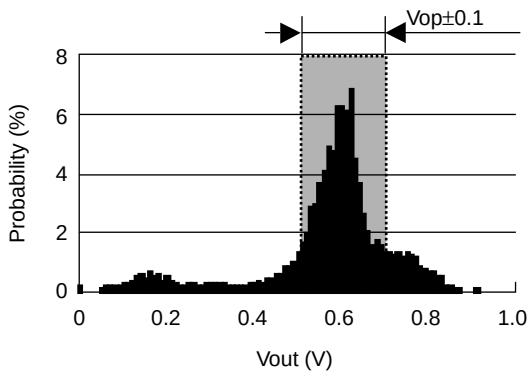


Fig. 12 Histogram of Vout controlled by PRISM

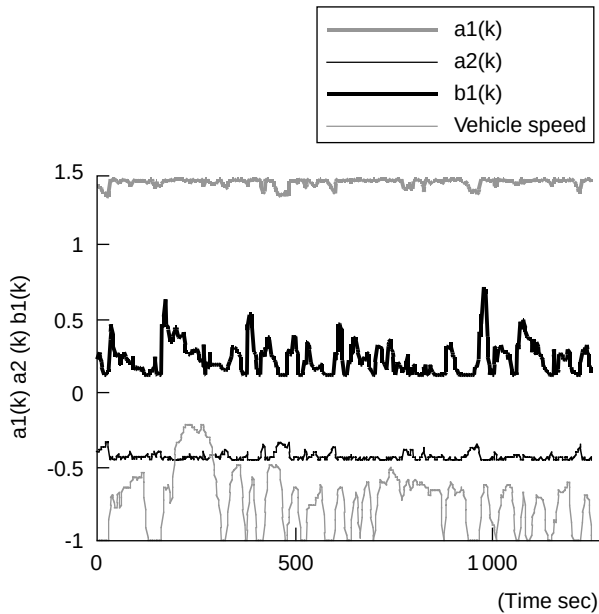


Fig. 13 Identification results for q in the FTP mode

5.1.2 Verification of adaptability with respect to catalyst aging conditions

In order to evaluate stability with respect to catalyst aging conditions, further Vout data is acquired using prototype vehicles with 0 mile and 100,000 mile equivalent aged catalysts. Table 1 is a comparison of the Vout probability in the range of $V_{op} \pm 0.1V$ under the three

 Table 1 Probability of Vout within the range of $V_{op} \pm 0.1V$

Equivalent aging condition of catalyst	0	50 000	100 000
Probability	78.9%	74.3%	81.0%

catalyst aging conditions. The difference of Vout probability in Table 1 is within 5%, which is a very small range. Therefore, it was verified that PRISM has superior adaptability with respect to catalyst aging conditions.

5.2 Effect on Emissions Reduction

In order to evaluate the emissions reduction effects of PRISM, emissions in the FTP mode are measured using the above mentioned prototype vehicle with the catalyst aged to an equivalent of 100,000 miles. The emissions as controlled by PRISM and the conventional method are compared in Table 2.

In Table 2, compared to the conventional method, PRISM reduces CO, NMHC and NOx by 34%, 32% and 42% respectively. This confirms that PRISM has greatly improved the emissions reduction effect.

In order to evaluate emission stability with respect to catalyst aging conditions, further FTP mode emissions were measured under catalyst aging conditions equivalent to 50,000, 100,000 and 300,000 miles. Fig. 14 shows normalized emissions under each of the catalyst aging conditions based on the 100,000-miles emissions. In the graph, when comparing 100,000 mile and 400,000 mile equivalents, CO increases by 60%. However, HC increased

Table 2 Comparison of FTP mode emissions for PRISM and conventional control

	CO	NMHC	NOx
Conventional control	0.105	0.022	0.071
PRISM	0.069	0.015	0.041
Improved ratio	34%	32%	42%

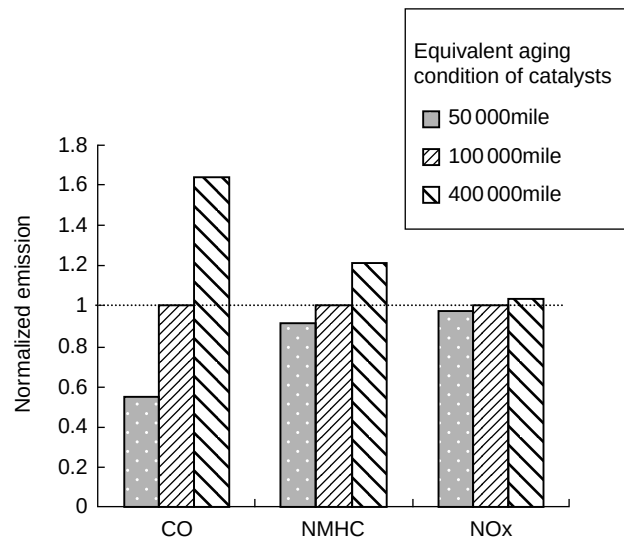


Fig. 14 PRISM emissions robustness

by approximately 20% and NO_x by a mere 3%. This shows that PRISM has sufficient emissions stability with respect to catalyst aging and it verifies the use of PRISM as an appropriate emissions reduction concept.

6. Summary

By applying PRISM, which integrates an identifier, predictor, and adaptive sliding-mode controller to secondary O₂ feedback, Vout control was achieved as follows.

- 1) Compared with the conventional method, Vout to Vop controllability is doubled.
- 2) Regardless of catalyst aging conditions, Vout probability in the range of $Vop \pm 0.1V$ was maintained at 74% or better. These provide the following effects on emissions.
- 1) Compared with the conventional method, FTP mode emissions were reduced by approximately 32 – 42%.
- 2) The emission stability with respect to catalyst aging conditions was dramatically improved.

References

- 1) Yasui, Akazaki, Ueno, and Iwaki: Adaptive Sliding Mode Control For Secondary O₂ Feedback, HONDA R&D Technical Review Vol.11 No.1, p.65-71 (1999)
- 2) Yasui, Akazaki, Ueno, and Iwaki: Adaptive Sliding Mode Control For Secondary O₂ Feedback – A Second Report, HONDA R&D Technical Review Vol. 11 No. 2, p.51-56 (1999)
- 3) Ohata, A., Masu, M., and Inoue, T.: Model Based Air-Fuel Control for Reducing Exhaust Gas Emissions, SAE Paper 950075 (1995)
- 4) Yatabe, H., Tai, H., and Matsuura, M.: Air-to-Fuel Ratio of Gas Engines Using Response Characteristics of Three-Way Catalysts Under Dynamic Operation, SAE Paper 910083 (1991)
- 5) Harada: Automotive Control Technology, Tokyo, Asakura Publishing, 1997
- 6) Katayama: Introduction to System Identification, Tokyo, Asakura Publishing, 1994, p.196
- 7) Nonami, Den: Sliding Mode Control, Tokyo, Corona Ltd. 1994, p.263
- 8) Yasui, Y., Akazaki, S., Ueno, M., Iwaki, Y.: Secondary O₂ Feedback Using Prediction and Identification Sliding Control, SAE Paper, 2000-01-0936 (2000)
- 9) Yasui, Y., Akazaki, S., Ueno, M., Iwaki, Y.: Secondary O₂ Feedback Using Prediction and Identification Sliding Control – Second Report –, SAE Paper, 2001-01-0264 (2001)
- 10) Maki, H., Hasegawa, Y., Akazaki, S., Komoriya, I., Nishimura, Y., and Hirota, T.: Real Time Control Using STR in Feedback System, SAE Paper 950007 (1995)
- 11) Adachi: System Identification Theory for the User, Tokyo, Transactions of SICE, 1993, p.222
- 12) Watabe: Dead Time System Control, Tokyo, Transactions of SICE, 1993, p.206

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