

Accurate Idle Speed Control for Gasoline Engines with Continuously Variable Valve Actuation

Kosuke HIGASHITANI*

Yuji YASUI*

Masahiro SATOH*

ABSTRACT

A gasoline engine with continuously variable valve actuation uses the valves instead of the throttle to control the suction air amount, thus reducing pumping loss. However, just a slight change in valve lift causes the suction air amount to vary greatly, which makes it difficult to accurately control idle speed when using conventional idle speed control.

Accordingly, in this research a new method of controlling the idle speed was proposed. This new idle speed control features coordination between suction air flow control and ignition timing control, each of which uses a two-degree-of-freedom sliding mode algorithm. Large deviations are corrected by air flow control, while small deviations are corrected by ignition timing control, thus realizing fine control of engine speed, which is necessary for reducing the idle speed.

As a result, it was possible to reduce the idle speed of a gasoline engine equipped with a continuously variable valve actuation, as well as increase the idle speed stability.

1. Introduction

Concern about global warming has increased in recent years, giving rise to social demands for reduced CO₂ emissions and increasing the importance of enhancing automobile fuel efficiency. As a result, gasoline engines with continuously variable valve actuation are garnering attention as a technology that increases fuel efficiency⁽¹⁾⁻⁽³⁾.

A gasoline engine with continuously variable valve actuation uses the valves instead of the throttle to control suction air amount, which reduces pumping loss. On the other hand, the airflow amount becomes more sensitive to even slight changes in the valve lift compared to conventional gasoline engines with throttles. This makes it a challenge to accurately control the engine speed using suction air flow, such as for idle speed control.

Conventional idle speed control consists of the ignition timing control and suction air control based on independent PI control. Therefore, the ignition timing and suction air controls interfere with

each other, resulting in overshoot with respect to changes in the target value.

To resolve this issue, conventional idle speed control uses a method that stops feedback and performs preset open-loop control when the target value changes in the downward direction or the engine speed drops. However, robustness (stability) with respect to parts deterioration is an issue with this method.

Therefore, it is necessary to construct a closed-loop idle speed control that does not produce overshoot when the target value changes or when recovering to the target idle speed after deviation occurs for some reason.

Sliding mode control⁽⁴⁾, which is a type of robust control, is one method that has recently been applied to engines^{(5),(6)} and other devices⁽⁷⁾.

Therefore, this study designed a new idle speed control based on cooperation between two types of sliding mode control to lower the idle speed of a gasoline engine with continuously variable valve actuation.

* Automobile R&D Center

2. Accurate Cooperative Two-Input Idle Speed Control

Accurately Cooperative Two-input Idle speed Control (ACTIC) was devised to lower the idle speed of a gasoline engine with continuously variable valve actuation.

In ACTIC, the control of suction air and ignition timing applied a two-degree-of-freedom sliding mode algorithm to accurately control the engine speed. In addition, cooperative control is realized between the suction air and ignition timing controls to prevent the two types of control from interfering with each other. An overview of this two-degree-of-freedom sliding mode control and cooperative control is described below.

2.1. Two-Degree-of-Freedom Sliding Mode Control

Two-degree-of-freedom sliding mode control is a sliding mode control that can separately designate the target value response speed and the deviation convergence speed. The target value response speed is designated using a target value filter, and the deviation convergence speed is designated using a switching function.

Labeling the engine speed as N_E and the set point of idle speed as N_r , the target value N_f used by sliding mode control is calculated using the target value filter shown in Eq. (1).

$$N_f(k) = -Pole_f N_f(k-1) + (1 + Pole_f) N_r(k) \quad (1)$$

The N_f behavior can be designated by the filter ratio $Pole_f$ of the target value filter. Therefore, the target value response behavior in sliding mode control can also be designated by using this N_f as the control target value.

With sliding mode control, the deviation $E_{NE}(k)$ between the target value $N_f(k-1)$ and the engine speed $N_E(k)$ is obtained using Eq. (2). The switching function $\sigma_{NE}(k)$ is defined as shown in Eq. (3).

$$E_{NE}(k) = N_E(k) - N_f(k-1) \quad (2)$$

$$\sigma_{NE}(k) = E_{NE}(k) + Pole E_{NE}(k-1) \quad (3)$$

Figure 1 shows a phase plane with $E_{NE}(k)$ and $E_{NE}(k-1)$ as the respective coordinate axes. The straight line where the switching function σ_{NE} becomes equal to zero on this phase plane is called the switching line.

Sliding mode control performs control so that the combination of $E_{NE}(k)$ and $E_{NE}(k-1)$ (hereafter the “deviation state”) is restricted to the switching line, and the deviation state is then converged along the switching line to the phase plane origin. In other words, the deviation $E_{NE}(k)$ is converged to zero. Here, the switching line is expressed by Eq. (4) based on the relationship between $E_{NE}(k)$ and $E_{NE}(k-1)$. In addition, $Pole$ is set within the range given by Eq. (5).

$$E_{NE}(k) = -Pole E_{NE}(k-1) \quad (4)$$

$$-1 < Pole < 0 \quad (5)$$

Therefore, the deviation convergence speed can be designated by $Pole$, which is the switching line gradient.

2.2. Cooperative Control

To achieve cooperation between suction air control and ignition timing control in ACTIC, the target value filter that designates the target value response speed and the switching function that specifies the deviation convergence speed are shared by both controls. In

addition, cooperative control is achieved by using the following characteristics of suction air control and ignition timing control.

Ignition timing control

- No dead time and little response delay
- Small N_E change width
- High N_E control resolution

Suction air control

- Dead time and large response delay
- Large N_E change width
- Low N_E control resolution

The two controls achieve cooperation by using these characteristics to switch the initiative control as follows.

- Tracking to large target changes and reducing large deviations
→ Suction air control is the initiative control.
- Tracking to small target changes and reducing small deviations
→ Ignition timing control is the initiative control.

3. Control Design

Figure 2 shows the ACTIC system diagram. The details of ignition timing control, suction air control and cooperative control are described below.

3.1. Ignition Timing Control

Ignition timing control comprises a sliding mode controller consisting of the reaching law input $U_{rch_ig}(k)$ and adaptive law input $U_{adp_ig}(k)$. The forgetting integration ratio λ is introduced to the adaptive law input $U_{adp_ig}(k)$ in order to gradually return to the pre-decided ignition timing when idling after converging to the target value. This avoids the need to maintain the ignition timing in an excessively retarded state, and suppresses the corresponding drop in fuel efficiency. The calculation formulas are as follows.

$$U_{sl_ig}(k) = U_{rch_ig}(k) + U_{adp_ig}(k) \quad (6)$$

$$U_{rch_ig}(k) = K_{rch_ig} \sigma_{NE}(k) \quad (7)$$

$$U_{adp_ig}(k) = K_{adp_ig} \sigma_{NE}(k) + \lambda U_{adp_ig}(k-1) \quad (8)$$

K_{rch_ig} , K_{adp_ig} : Feedback gain

λ : Forgetting integration ratio ($0 < \lambda < 1$)

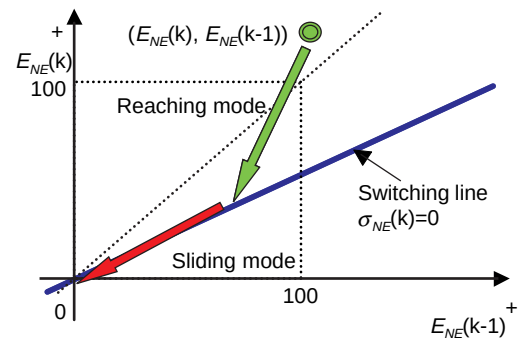


Fig. 1 Sliding mode control

3.2. Suction Air Control

Suction air control consists of a sliding mode controller that is calculated based on a controlled object model that represents the input/output relation, and an adaptive disturbance observer that corrects the controlled object model representing the input/output relation. The details of the controlled object model, sliding mode controller and adaptive disturbance observer are described below.

3.2.1. Controlled object model

The controlled object model that expresses the relationship between engine speed $N_E(k)$ and control input $U_{sl_ar}(k)$ is defined as shown in Eq. (9).

$$\begin{aligned} N_E(k+1) = & \quad (9) \\ & a_1 N_E(k) + a_2 N_E(k-1) + b_1 U_{sl_ar}(k) + b_2 U_{sl_ar}(k-1) + c_1(k) \\ & a_1 a_2 b_1 b_2 : \text{Model parameters} \\ & c_1(k) : \text{Estimated disturbance value} \end{aligned}$$

The model parameters a_1 , a_2 , b_1 and b_2 are predetermined by system identification. In addition, the estimated disturbance value c_1 is calculated consecutively by the adaptive disturbance observer.

3.2.2. Adaptive disturbance observer

The adaptive disturbance observer is calculated based on the deviation $E_{dov_ar}(k)$ between the $N_E(k)$ and the $N_{E_hat}(k)$ calculated using the controlled object model prescribed by Eq. (9). In other words, the c_{1_ar} that results in the minimum difference between N_{E_hat} and N_E is estimated by the fixed gain method used by adaptive control. The calculation formulas are as follows.

$$\begin{aligned} N_{E_hat}(k) = & \\ & a_1 N_E(k-1) + a_2 N_E(k-2) + b_1 U_{sl_ar}(k-1) \\ & + b_2 U_{sl_ar}(k-2) + c_{1_ar}(k-1) \end{aligned} \quad (10)$$

$$E_{dov_ar}(k) = N_E(k) - N_{E_hat}(k) \quad (11)$$

$$c_{1_ar}(k) = c_{1_ar}(k-1) + \frac{P_{ar}}{1 + P_{ar}} E_{dov_ar}(k) \quad (12)$$

P_{ar} : Fixed gain

The adaptive disturbance observer absorbs the modeling error of the controlled object model prescribed by Eq. (9) by estimating the disturbance element c_{1_ar} . This achieves a high robustness with respect to disturbances and parts deterioration.

3.2.3. Sliding mode controller

The sliding mode controller used by suction air control consists of the reaching law input $U_{rch_ar}(k)$ and the equivalent law input $U_{eq_ar}(k)$. The calculation formulas are as follows.

$$U_{sl_ar}(k) = U_{rch_ar}(k) + U_{eq_ar}(k) \quad (13)$$

$$U_{rch_ar}(k) = K_{rch_ar} \sigma_{NE}(k) \quad (14)$$

$$\begin{aligned} U_{eq_ar}(k) = & \\ & \frac{1}{b_1} \{ (1 - a_1 - Pole) N_E(k) + (Pole - a_2) N_E(k-1) \\ & + N_f(k) + (Pole - 1) N_f(k-1) - Pole N_f(k-2) \\ & - b_2 U_{sl_ar}(k-1) - c_1(k) \} \end{aligned} \quad (15)$$

K_{rch_ar} : Feedback gain

$U_{eq_ar}(k)$ has a function that constrains the deviation state onto the switching line prescribed by the switching function. The estimated disturbance value c_{1_ar} is inserted to add a disturbance compensation function to this $U_{eq_ar}(k)$.

Ignition timing control performs disturbance compensation using $U_{adp_ig}(k)$, which is based on the integration value of the switching function. In contrast, suction air control performs disturbance compensation by $U_{eq_ar}(k)$, which uses the $c_{1_ar}(k)$ estimated by the adaptive disturbance observer. c_{1_ar} estimates the disturbance using the aforementioned fixed gain method, so the disturbance

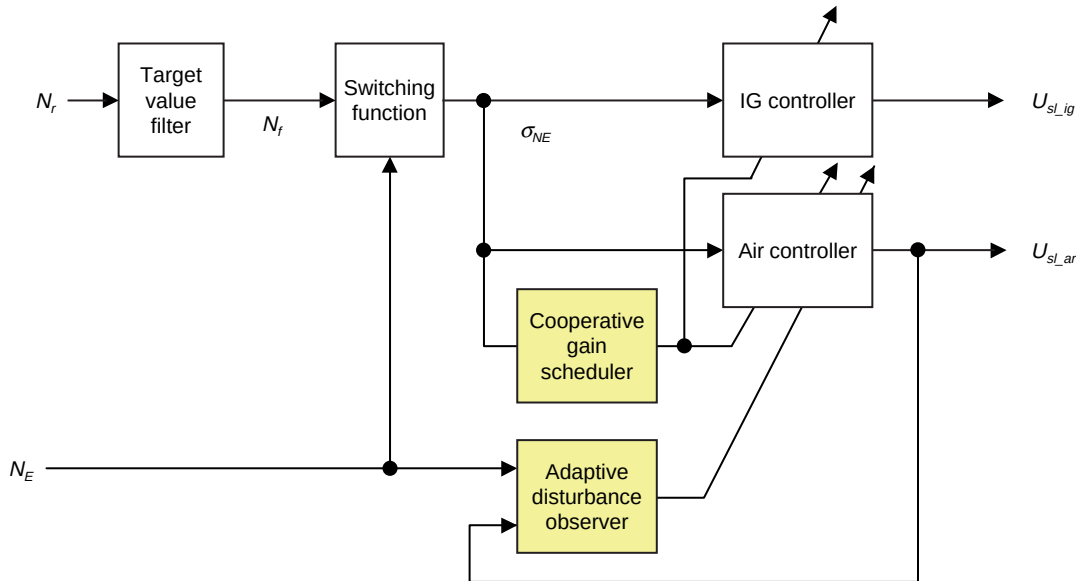


Fig. 2 System diagram of ACTIC

compensation responsiveness is better than for $U_{adp_ig}(k)$, which performs disturbance compensation using an integrator.

3.3. Cooperative Gain Scheduler

ACTIC achieves cooperative control by determining the initiative control and performing the appropriate switching with a cooperative gain scheduler.

As shown in Fig. 3, the initiative control is judged to be ignition timing control in areas with a small switching function value σ_{NE} , and suction air control in areas with a large switching function value σ_{NE} .

In addition, a low suction air control gain is set in the area where ignition timing control is the initiative control, and a low ignition timing control gain is set in the area where suction air control is the initiative control. The initiative control is switched by changing the control gain in this manner. Figures 4 and 5 show the relation between the ignition timing control gain and the suction air control gain.

4. Vehicle Test Results

The stability, responsiveness and disturbance rejection capability of ACTIC and conventional idle speed control were compared. In addition, the behavior after engine start and fuel consumption were compared with and without forgetting integration to illustrate the effects of the ACTIC forgetting integration. The results are described below.

4.1. Stability

Figure 6 compares the stability of ACTIC and conventional idle speed control in the unloaded condition with an idle speed set point of 600 rpm. These results show that ACTIC has higher stability than conventional idle speed control.

4.2. Responsiveness and Disturbance Rejection Capability

To compare responsiveness and disturbance rejection capability, the engine speed behavior was measured when the idle speed set point was changed from 600 rpm to 720 rpm while simultaneously

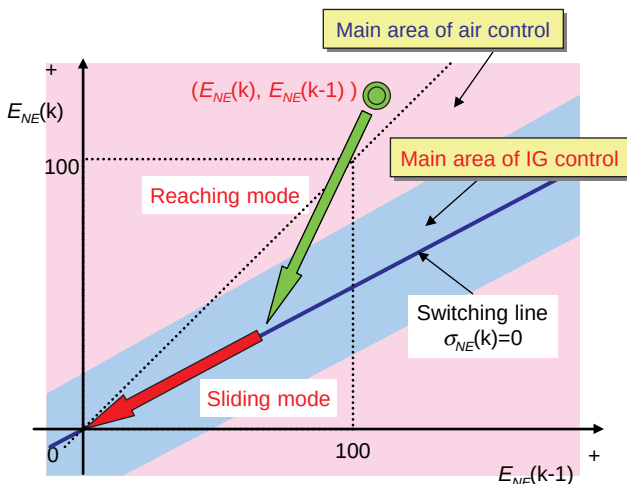


Fig. 3 Main controller switching

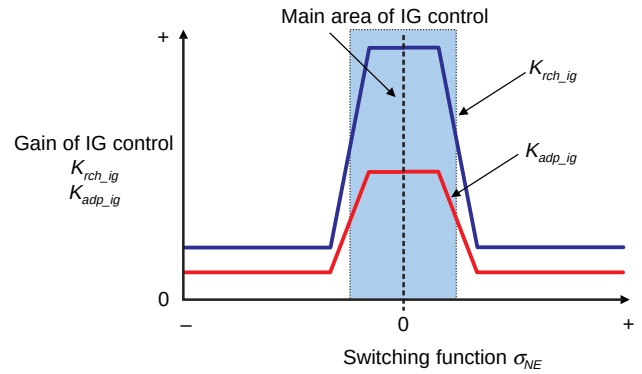


Fig. 4 Gain scheduling of ignition timing control

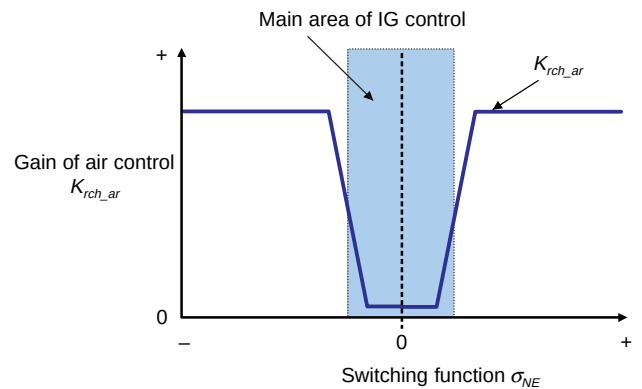


Fig. 5 Gain scheduling of suction air control

applying a load input (air conditioning load). Figure 7 shows the results.

Conventional idle speed control was able to suppress the drop in engine speed caused by the air conditioning load (disturbance). However, the engine speed overshoot the set point of idle speed, resulting in wasteful over-revving. This overshoot is caused by interference between ignition timing control and suction air control.

Comparatively, ACTIC was able to suppress the drop in engine speed caused by the air conditioning load (disturbance) in the same manner as conventional idle speed control. In addition, ACTIC also reduced engine speed over-revving due to overshoot compared to conventional idle speed control.

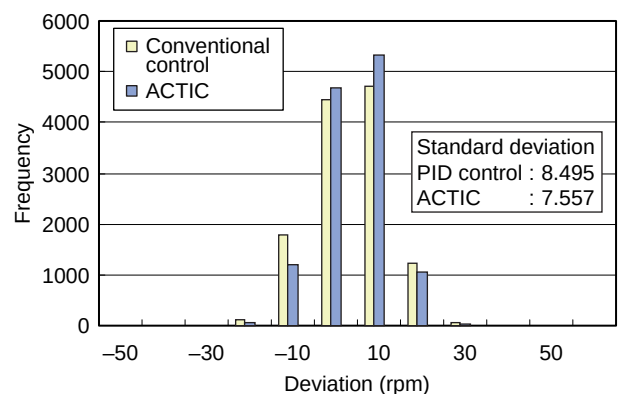


Fig. 6 Comparison of stability with idle speed control

These results show that ACTIC reduces interference between suction air control and ignition timing control using cooperative control, and realizes higher target value responsiveness and disturbance rejection capability than conventional idle speed control.

4.3. Forgetting Integration

The behavior after engine start was measured with and without forgetting integration to confirm its effects. Figure 8 shows the engine speed, ignition timing and valve lift behavior after engine start until the engine speed settled down to the idle speed set point of 600 rpm.

Forgetting integration caused the ignition timing to return to the preset ignition timing, and the valve lift also moved toward a lower lift at the same time.

Next, Fig. 9 compares the standard deviation of the engine speed after converging to the idle speed set point of 600 rpm with and without forgetting integration.

These results show that the idle speed stability decreases without forgetting integration. The idle speed control stability decreases because the ignition timing is excessively retarded, causing the torque fluctuations to increase.

In addition, Fig. 10 compares the fuel consumption after converging to the idle speed set point of 600 rpm with and without forgetting integration.

The fuel consumption increases without forgetting integration compared to that with forgetting integration. This is also caused by excessive retardation of the ignition timing.

These results confirm that the introduction of forgetting integration can suppress the drop in fuel efficiency when idling and also avoid reduced stability due to excessive ignition timing retard.

5. Conclusion

A new idle speed control (ACTIC) that cooperatively controls the ignition timing and suction air flow was introduced to lower the idle speed in a gasoline engine with continuously variable valve actuation. Vehicle test results provided the following information.

- (1) Stability is enhanced at an idle speed of 600 rpm.
- (2) There is no interference between ignition timing control and suction air control, creating enhanced responsiveness to target speed changes and disturbance rejection capability.
- (3) The forgetting integration of ignition timing control can suppress excessive retardation of the ignition timing, which enhances both idle speed stability and fuel efficiency.

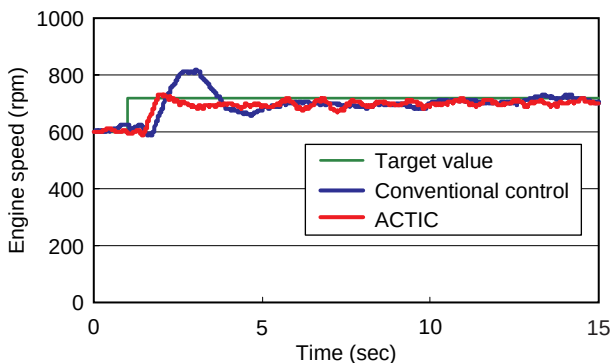


Fig. 7 Idle speed control response when disturbance is input

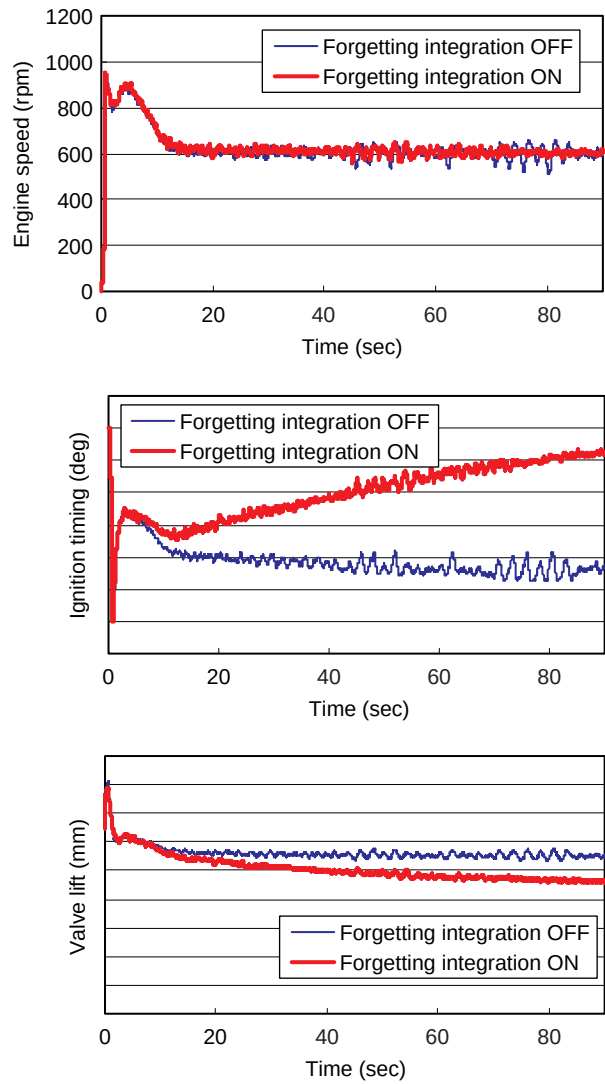


Fig. 8 Influence of forgetting integration on ignition timing and inlet valve lift behavior

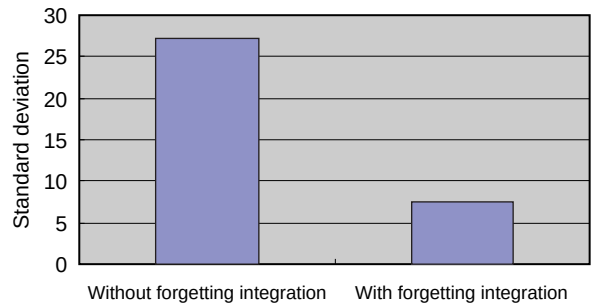


Fig. 9 Influence of forgetting integration on idle speed stability

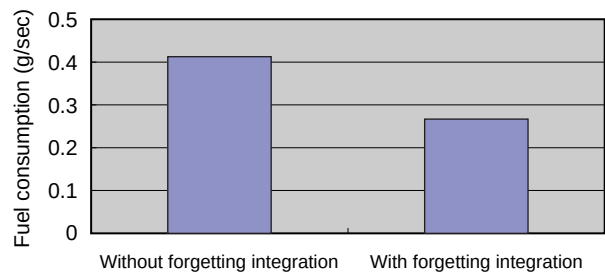


Fig. 10 Influence of forgetting integration on fuel consumption

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■ Authors ■



Kosuke HIGASHITANI



Yuji YASUI



Masahiro SATOH