

Development of Intake Air Pressure Sensor-less Fuel Injection System for Small Motorcycles

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ABSTRACT

An electronically controlled fuel injection system for small motorcycles was developed without an intake air pressure sensor to reduce costs. In a fuel injection system, the intake air pressure sensor performs the three functions of measuring the amount of intake air in minute throttle-opening range, measuring the atmospheric pressure, and distinguishing the engine stroke. This study replaced these functions with a new learning control system that applies O₂ feedback control, and engine-stroke distinction control based on detection of crankshaft rotation speed fluctuation. This new learning control system defines the operational condition compensation coefficient K_{bu} , which covers operational conditions such as atmospheric pressure and conditional variations among completed engines, and uses this coefficient in the fuel injection quantity correction function. This enabled proper fuel injection quantity control without depending on intake air pressure sensor functions. In addition, storing K_{bu} in an Engine Control Unit (ECU) enabled proper air fuel ratio correction even when O₂ feedback control is inactive, such as when the engine is cold immediately after starting or during transient operation. The engine-stroke distinction function enabled stroke distinction equal to that of the conventional system by changing the method from measurement of the difference in intake air pressure between engine strokes to detection of crankshaft rotation speed fluctuation between engine strokes. This technology realized a simplified system that maintains the same performance for exhaust emissions and fuel economy without an intake air pressure sensor.

1. Introduction

As concern about environmental issues grows worldwide, demands are increasing to reduce exhaust emissions. Motorcycles are no exception to this, and the shift from carburetor-based fuel supply systems to electronically controlled fuel injection systems (hereafter “current FI systems”) is progressing as an effective means of reducing motorcycle exhaust emissions. Compared to carburetors, current FI systems can more accurately control the air fuel ratio in response to changes in the intake air temperature and atmospheric pressure. However, this type of control requires multiple sensors to measure factors such as the amount of intake air, intake air temperature, atmospheric pressure, cam phase, crankshaft phase, and concentration of residual oxygen in the exhaust gas. As a result, there is the issue that the system is more complex and expensive than a carburetor. Simple and low-cost systems are more strongly demanded in particular for small motorcycles compared to cars and large motorcycles.

Various studies thus far have sought to reduce costs by eliminating the secondary air supply system⁽¹⁾, combining various sensors with the throttle body⁽²⁾, realizing heater-less compact O₂ sensors⁽³⁾, and reducing injector and fuel pump sizes^{(4), (5)}. However, few studies have focused on simplifying the system by integrating sensor functions.

This study integrated sensor functions with the aim of simplifying the system. The functions of the intake air pressure sensor were instead performed using a new learning control system that uses O₂ feedback control and a stroke distinction function that detects crankshaft rotation speed fluctuation. This enabled maintaining the same performance for exhaust emissions and fuel economy without an intake air pressure sensor.

2. Overview of Test Motorcycle and Current FI System

Figure 1 and Table 1 show an external view and the main specifications of the test motorcycle WAVE110.

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Table 1 Engine specifications of test motorcycle

Item		Specifications
Engine type		4-stroke single-cylinder
Cooling system		Air-cooled
Bore × Stroke (mm)		50.0 × 55.6
Engine displacement (cm ³)		109.1
Compression ratio		9.0
Valve train		SOHC
Valve diameter (mm)	Inlet	φ 25.5 × 1
	Exhaust	φ 21.0 × 1
Maximum Horsepower (kW/r/min)		6.18/7500
Maximum torque (Nm/r/min)		8.15/5500

The WAVE110 is a small motorcycle equipped with an air-cooled 4-stroke single-cylinder 110 cm³ engine that complies with Thailand's sixth exhaust emission standards, which are equivalent to EURO3 exhaust emission standards.

Figure 2 shows an external view of the throttle body. The intake air pressure sensor eliminated in this study is mounted inside a sensor unit integrated with the throttle body.

Figure 3 shows the current FI system configuration of the test motorcycle.

The current FI system mounted in the WAVE110 does not have a startup air device. It complies with Thailand's



Fig. 1 Test motorcycle

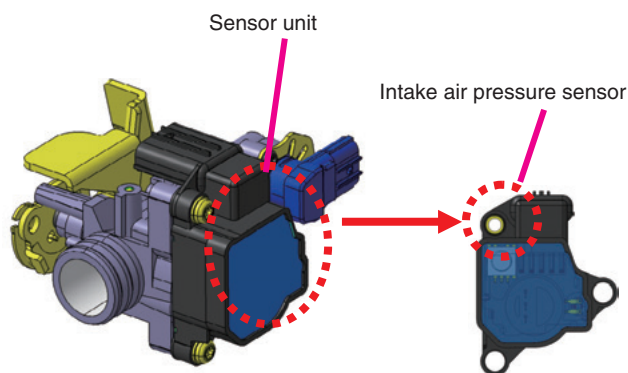


Fig. 2 External view of throttle body

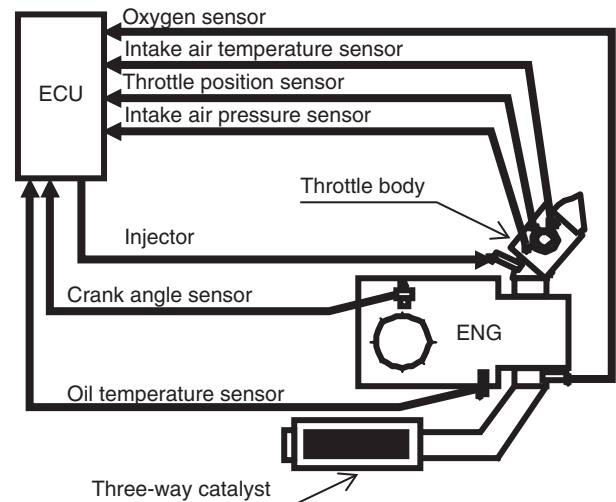


Fig. 3 Basic diagram of current FI system

sixth exhaust emission standards, which are equivalent to EURO3 exhaust emission standards, using a system that expands O₂ feedback control to the idle speed range and a three-way catalyst.

3. Investigation of Simplification

Elimination of sensors used in current FI systems was investigated as a means of simplification. Current FI systems determine the basic fuel injection quantity according to the amount of intake air obtained by direct measurement or indirect measurement. In the test motorcycle, the amount of intake air is not measured directly using an air flow sensor, and is instead measured indirectly as follows. In the minute throttle-opening range, the speed density method is used to calculate the amount of intake air from the intake air pressure and the engine rotation speed. Beyond the minute throttle-opening range, the throttle speed method is used to calculate the amount of intake air from the throttle-opening angle and the engine rotation speed⁽⁶⁾. In addition, multiple sensors are mounted to perform correction control in response to changes in the intake air temperature and atmospheric pressure, the engine warm-up state, and other factors. The intake air temperature sensor, O₂ sensor, engine oil temperature sensor, and crank angle sensor respectively measure the intake air temperature, concentration of residual oxygen in the exhaust gas, engine oil temperature, and crankshaft rotation speed. That is to say, each sensor measures a different subject, so replacement by other sensors is thought to be a challenge. On the other hand, while the throttle position sensor and intake air pressure sensor measure different subjects, these sensors perform the same function to indirectly measure the amount of intake air. Therefore, the feasibility was investigated of simplifying the system by eliminating one of these sensors and having the other sensor perform part of the eliminated sensor's functions.

4. Determination of the Sensor to be Eliminated

The feasibility of eliminating the throttle position sensor or the intake air pressure sensor was investigated, focusing on the functions of each sensor. The main functions of the throttle position sensor are as follows.

- (1) Measurement of the amount of intake air beyond the minute throttle-opening range by the throttle speed method;
- (2) Determination of the throttle position (detection of full close, full open, and other operating states);
- (3) Acceleration decisions (correction to increase the fuel quantity when accelerating and correction to advance the ignition timing angle); and
- (4) Determination of ignition timing.

Investigation of the issues involved in eliminating the throttle position sensor found that:

- The accuracy drops somewhat, but the amount of intake air beyond the minute throttle-opening range can be measured by the intake air pressure sensor even in the current system.
- The throttle position judgment is used to determine idling, full open running and other operating states. Therefore, substitution requires the addition of a throttle switch, so the system cannot be simplified.
- Motorcycles require good acceleration response, so the throttle position sensor is the sensor most suited to detecting operating conditions. This makes it a challenge to construct a means of replacing the functions of acceleration decisions and determination of ignition timing.

As a result, it was decided not to eliminate the throttle position sensor.

On the other hand, the main functions of the intake air pressure sensor are as follows.

- (1) Measurement of the amount of intake air in the minute throttle-opening range by the speed density method;
- (2) Estimation of atmospheric pressure from the intake air pressure; and
- (3) Engine stroke distinction.

Similar investigation of the issues involved in eliminating the intake air pressure sensor found that:

- The accuracy drops somewhat, but the amount of intake air in the minute throttle-opening range can be measured by the throttle position sensor even in the current system.
- The atmospheric pressure is estimated to correct the fuel injection quantity in response to changes in the atmospheric pressure, but that correction can be replaced with other means for correcting fuel injection quantity.
- The engine-stroke distinction function can be replaced by detecting the angular velocity of the crankshaft, which fluctuates according to each stroke.

As a result, it was thought possible to construct a system without the intake air pressure sensor.

5. Intake Air Amount Characteristics and Issues Involved in Eliminating the Intake Air Pressure Sensor

To eliminate the intake air pressure sensor it is necessary to replace the three functions performed by the intake air pressure sensor as described above. Investigations to extract the issues involved in this replacement first focused on the relationship between the throttle-opening angle and the amount of intake air.

Figure 4 shows a typical example of the amount of intake air and intake air pressure characteristics relative to the throttle-opening angle. In the minute throttle-opening range (throttle opening: 7.5 deg or less), there is little change in the amount of intake air but the intake air pressure changes greatly. On the other hand, beyond the minute throttle-opening range (throttle opening: 7.5 deg or more), the amount of intake air changes greatly but there is little change in the intake air pressure. This means that the speed density method can more accurately measure the amount of intake air in the minute throttle-opening range, and the throttle speed method can more accurately measure the amount of intake air beyond the minute throttle-opening range. Generally, both the speed density method and the throttle speed method are used in motorcycles, and various settings are made in accordance with these characteristics. Therefore, when eliminating the intake air pressure sensor, the first issue is to maintain accurate measurement of the amount of intake air in the minute throttle-opening range.

Next, issues related to adjustment of the engine idle speed are described.

Figure 5 shows the structure of a throttle body with a bypass. The base model throttle body has a bypass that enables manual adjustment of the amount of air passing through the throttle in order to adjust the engine idle speed. The air taken into the engine is divided into two passages: the main passage through the throttle valve and the bypass.

Figure 6 shows an example of the intake air

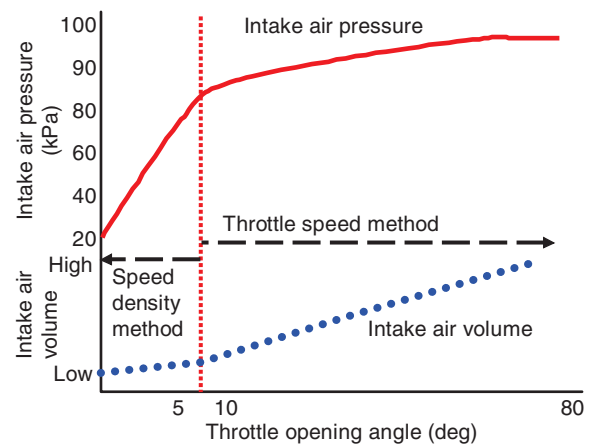


Fig. 4 Characteristics of intake air pressure and amount of intake air in relation to throttle opening angle

composition characteristics relative to the throttle-opening angle. At a throttle opening of 0 deg, most of the intake air passes through the bypass, and the amount of the bypass air decreases as the throttle valve opens further. The speed density method can measure changes in the amount of intake air due to adjusting the bypass as changes in the intake air pressure. This enables maintaining accurate measurement of the amount of intake air. On the other hand, changes in the amount of intake air do not appear as changes in the throttle-opening angle, so the throttle speed method is unable to maintain this measurement accuracy. Therefore, the second issue is how to measure changes in

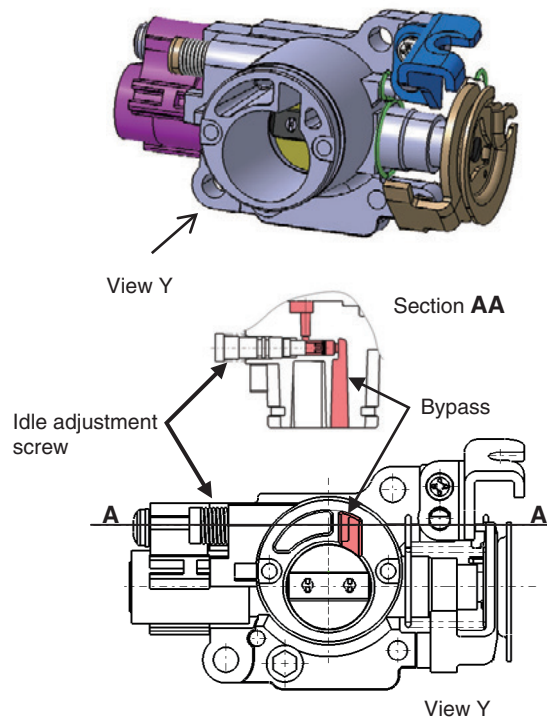


Fig. 5 Throttle body and bypass structure

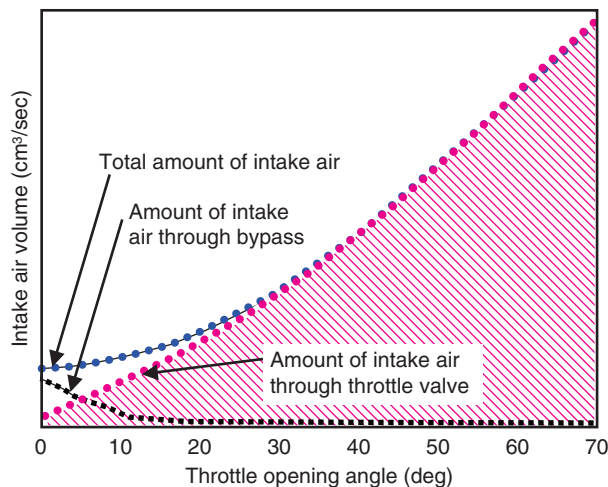


Fig. 6 Amount of intake air in relation to throttle opening angle

the amount of intake air due to adjustment of the engine idle speed.

Next, the second function of the intake air pressure sensor is described: corrections relative to changes in atmospheric pressure. The intake air density changes according to changes in atmospheric pressure due to weather conditions or the altitude at which the motorcycle is running. To perform control to the proper air fuel ratio, the fuel injection quantity should be corrected in response to changes in the intake air density. Most current FI systems estimate the atmospheric pressure from the intake air pressure in order to perform correction. Therefore, the third issue when eliminating the intake air pressure sensor is how to maintain the accuracy of fuel injection quantity corrections in response to changes in atmospheric pressure.

Finally, the third function of the intake air pressure sensor is described: engine stroke distinction. In a 4-stroke single-cylinder engine, stroke distinction is normally performed immediately after starting the engine in order to inject the fuel at the proper timing. The engine-stroke distinction function of the current system uses the intake air pressure sensor signal, so the fourth issue when eliminating the intake air pressure sensor is how to maintain this stroke distinction function.

As described above, in order to replace the three functions of the intake air pressure sensor, the following four issues need to be considered.

- Maintaining accurate measurement of the amount of intake air in the minute throttle-opening range
- Maintaining accurate measurement of the amount of intake air when adjusting the engine idle speed
- Maintaining accurate correction of the fuel injection quantity in response to changes in atmospheric pressure
- Maintaining the engine-stroke distinction function

These can be broadly grouped into the following two items:

- (1) Maintaining accurate measurement of the amount of intake air and accurate correction of the fuel injection quantity
- (2) Maintaining the engine-stroke distinction function

Alternate methods of accomplishing these items were constructed.

6. Alternate Method of Maintaining Accurate Measurement of the Amount of Intake Air and Accurate Correction of the Fuel Injection Quantity

First, an alternate method is described of maintaining accurate measurement of the amount of intake air and accurate correction of the fuel injection quantity, which is the first item mentioned above.

6.1. Measures Using O₂ Feedback Control

Construction of an alternate method focused on the O₂

feedback control that is used to increase the purification performance of the three-way catalyst in current FI systems. In O_2 feedback control, it is detected whether the air fuel ratio is richer or leaner than the theoretical air fuel ratio based on the output voltage of the O_2 sensor which measures oxygen concentration in the exhaust emissions, and constantly makes small adjustments to the fuel injection quantity using the O_2 feedback coefficient (hereafter “ K_{O2} ”) to cancel out the rich and lean ratios and converge towards the theoretical air fuel ratio. Figure 7 shows an example of O_2 feedback control operation. O_2 feedback control enables correction of the fuel injection quantity using K_{O2} to supply the proper amount of fuel in response to changes in the amount of intake air in the minute throttle-opening range, changes in the amount of intake air due to engine idle speed adjustment, and changes in the air density due to changes in atmospheric pressure. That is to say, O_2 feedback control basically enables maintaining accurate measurement of the amount of intake air and accurate correction of the fuel injection quantity.

6.2. Measures when O_2 Feedback Control is Inactive

6.2.1. Issues when O_2 feedback control is inactive

O_2 feedback control enables maintaining accurate measurement of the amount of intake air and accurate correction of the fuel injection quantity. However, O_2 feedback control cannot be performed under all operating conditions.

O_2 feedback control cannot be performed under the following conditions:

- When the O_2 sensor is cold;
- While the engine is warming up;
- While the fuel injection is cut;
- During rapid acceleration; and
- Immediately after restarting the engine.

These conditions occur frequently during actual operation, so O_2 feedback control often cannot be

performed. At that time, the fuel injection quantity cannot be corrected in response to changes in the amount of intake air due to changes in engine conditions, adjustment of the engine idle speed, and changes in atmospheric pressure. Therefore, measures are needed for when O_2 feedback control is inactive.

6.2.2. Measures of addressing issues when O_2 feedback control is off

To deal with these issues, learning control was constructed using the operational condition compensation coefficient (hereafter “ K_{bu} ”) defined below. The basic approach of this learning control is as follows. The average value of K_{O2} during a given time period while O_2 feedback control is operating in actual atmospheric conditions, after stabilizing to the theoretical air fuel ratio, is defined as K_{O2ave} . The K_{O2} value that results in the theoretical air fuel ratio in standard atmospheric conditions is defined as the reference value K_{O2std} , and K_{bu} is calculated as the ratio of K_{O2ave} to K_{O2std} . When K_{bu} is stable, it is stored in the ECU memory as the learned value (hereafter “learned”) and applied to the basic fuel injection quantity. This learning control uses the learned K_{bu} to perform correction that matches the engine demands, enabling constant supply of the proper fuel injection quantity even under conditions when O_2 feedback control cannot be performed.

The K_{bu} calculation formula is shown below.

$$K_{bu} = K_{O2ave} / K_{O2std} \quad (1)$$

K_{bu} : Operational condition compensation coefficient

K_{O2} : O_2 feedback correction coefficient ($K_{O2} = 1.0$ when O_2 feedback control is inactive)

K_{O2ave} : Average value of O_2 feedback correction coefficient K_{O2} at the actual atmospheric pressure

K_{O2std} : O_2 feedback correction coefficient that results in the theoretical air fuel ratio at the standard atmospheric pressure

The K_{bu} obtained by this calculation formula was reflected to the formula used to calculate the fuel injection quantity.

This fuel injection quantity calculation formula is as follows.

$$T_{out} = Map_{th} \times K_{bu} \times K_{to} \times K_{O2} \quad (2)$$

T_{out} : Fuel injection quantity

Map_{th} : Basic fuel injection quantity in the throttle speed method

K_{to} : Oil temperature correction coefficient

When O_2 feedback control is active, K_{O2} is used to adjust towards the theoretical air fuel ratio in response to changes in the amount of intake air. When the K_{O2ave} calculated at

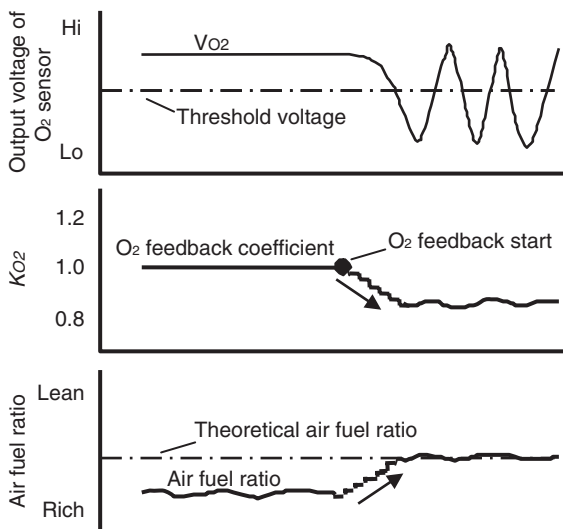


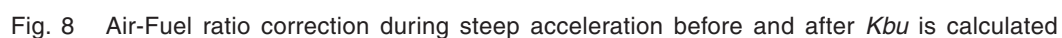
Fig. 7 O_2 feedback control operation

(1) The engine is cold when it starts, so the fuel injection quantity is generally increased as startup correction to stabilize the engine idle speed. $Kbu(0)$ represents the initial value. When the altitude, weather or other environmental conditions differ from the conditions set for the initial value, the target air fuel ratio may not be achieved after this startup correction ends.

- (2) The increase in the fuel injection quantity ends, and O_2 feedback control starts. The air fuel ratio is immediately corrected to the theoretical air fuel ratio, and at the same time $Kbu(n)$ is calculated from the Ko_2 average value. Kbu is updated from $Kbu(0)$ to $Kbu(n)$.
- (3) This $Kbu(n)$ value is stored in the nonvolatile memory as the learned value.
- (4) The engine is stopped. $Kbu(n)$ is retained because it is stored in the nonvolatile memory.
- (5) When the engine is restarted next, the $Kbu(n)$ value is read from the nonvolatile memory and used as the operational condition correction coefficient $Kbu(n)$ until O_2 feedback control starts. $Kbu(n)$ is updated at points (2) and (3), so control can be performed to a value near the target air fuel ratio even when O_2 feedback control is inactive.
- (6) When Ko_2 differs after O_2 feedback control starts, a new value $Kbu(n+1)$ is calculated.
- (7) When the $Kbu(n+1)$ value differs from $Kbu(n)$, $Kbu(n+1)$ is stored in the nonvolatile memory as the learned value.

Figure 10 shows the results of verifying the effects of fuel injection quantity correction by K_{bu} from the condition with the air fuel ratio shifted to the rich side during idling in a completed motorcycle.

- The left figure shows the condition before Kbu has been



learned, with the actual air fuel ratio shifted from the target air fuel ratio (theoretical air fuel ratio).

- The center figure shows the condition after Kbu is learned, with the air fuel ratio approaching the target air fuel ratio (theoretical air fuel ratio).
- The right figure shows the start of O_2 feedback control and convergence of the air fuel ratio to the theoretical air fuel ratio.

Figure 11 shows the changes in the Kbu value and the air fuel ratio when the atmospheric pressure is gradually lowered from approximately 100 kPa to approximately 65 kPa in the idling state. As the atmospheric pressure changes, a difference occurs between Ko_2 and Ko_2std , and Kbu is

updated. This operation is repeated so that Kbu tracks the change in atmospheric pressure, enabling control of the proper air fuel ratio even when operating at high altitudes.

These results show that the function to measure the amount of intake air can be maintained even without the intake air pressure sensor.

6.4. Enhancing the Accuracy of Correction by Kbu

This learning control system using Kbu is an effective control system that applies O_2 feedback control to support various operating environments and conditions. However, some consideration must be given to the bypass characteristics described above.

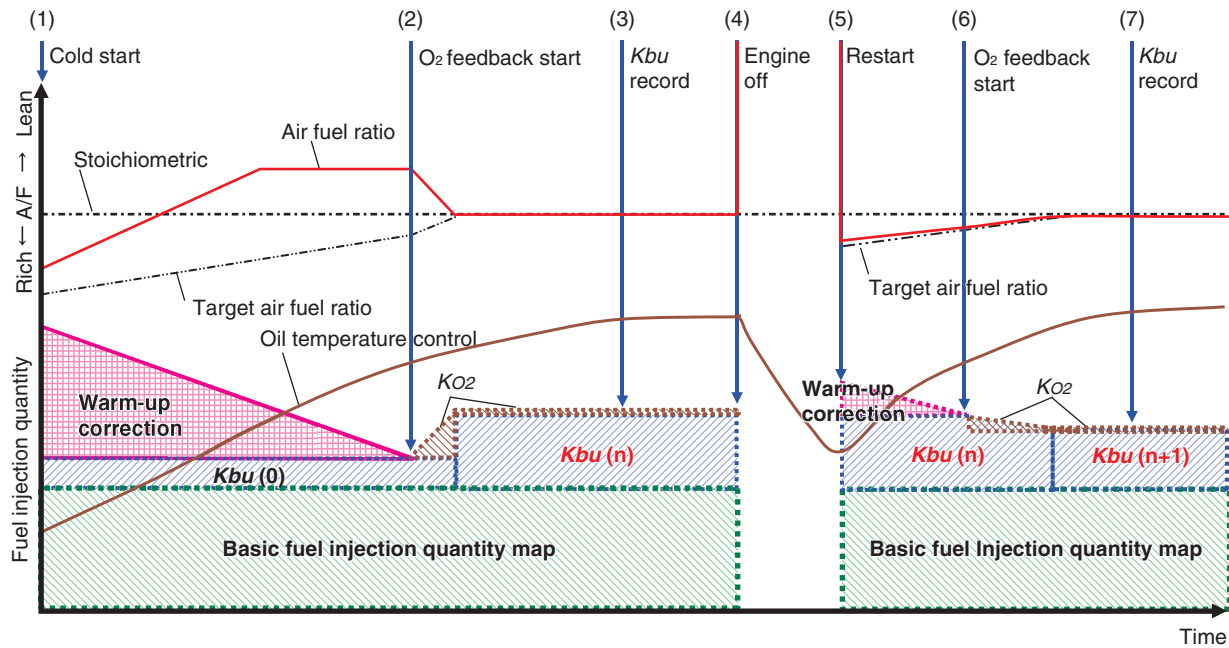


Fig. 9 Process to calculate and store Kbu and perform fuel injection control after cold start of engine

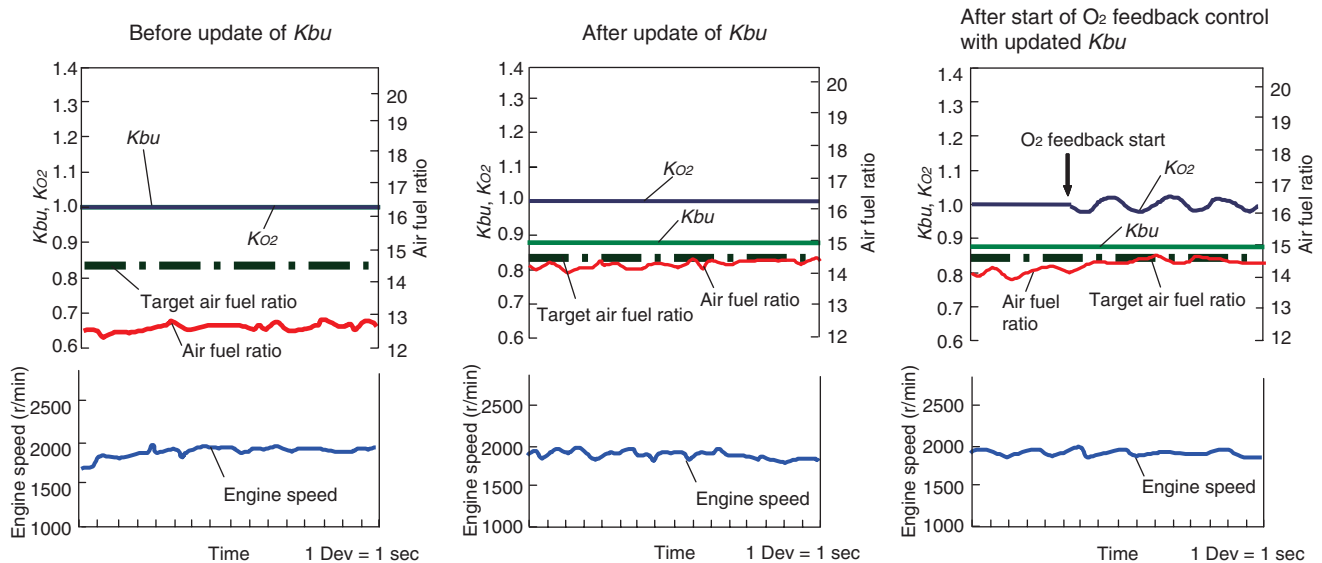


Fig. 10 Process to calculate and store Kbu and perform fuel injection control after cold start of engine

Figure 12 shows the change in the amount of intake air relative to the throttle-opening angle when the bypass is set to reduce the amount of intake air by 20% during idling. The 0% line is the baseline, and represents the state before adjusting the amount of idling intake air. When the amount of intake air during idling is reduced by 20%, the percentage of change in the amount of intake air relative to the total air increases as the throttle-opening angle approaches the minute throttle-opening range. Figure 13 shows the change in the K_{bu} value relative to the throttle-opening angle at that time. The 1.0 line is the baseline, and represents K_{bu} before adjusting the amount of idling intake air. K_{bu} represents

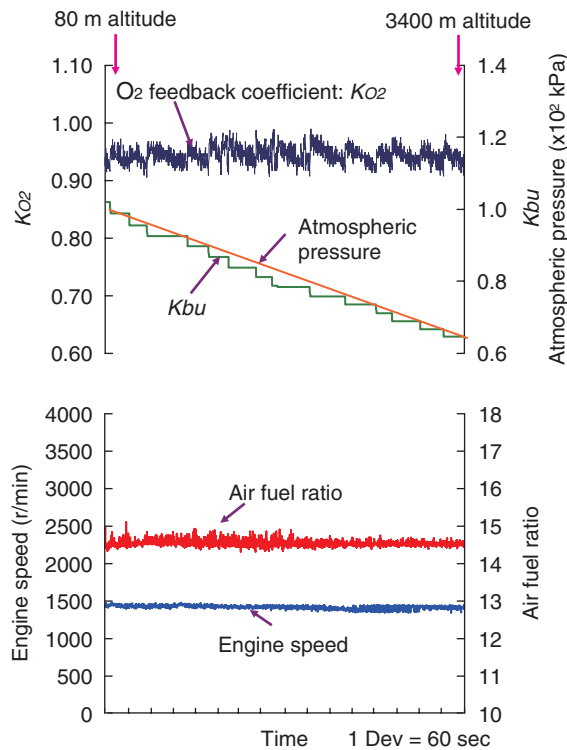


Fig. 11 Corrective effect by K_{bu} in response to changes in atmospheric pressure

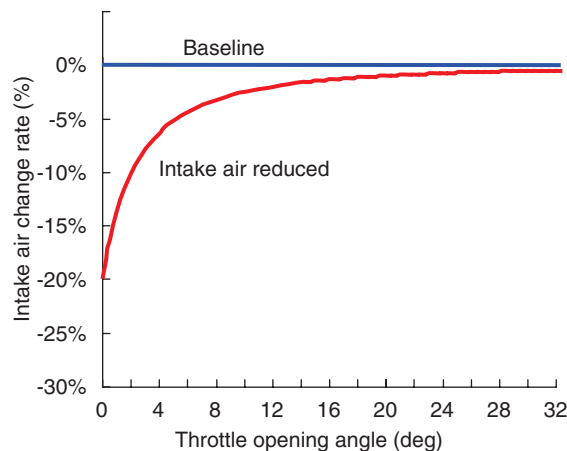


Fig. 12 Change rate of air intake when amount of intake air is reduced by 20% by bypass

the rate of change in the amount of intake air from its own definition, so it exhibits the same characteristics as the amount of intake air and shows the greatest change in the minute throttle-opening range. This means that accurate correction cannot be performed using only a single K_{bu} value when operating in the minute throttle-opening range. Therefore, to increase the accuracy of correction by K_{bu} , the K_{bu} calculation area was divided into multiple sections according to the throttle-opening angle.

Smaller K_{bu} calculation area divisions mean less change in K_{bu} within a single division, which enables minimizing the discrepancy between the theoretical air fuel ratio and the actual air fuel ratio. However, in transient operating states where the throttle-opening angle changes constantly, the time that the measurement point remains within a single K_{bu} calculation area shortens if the K_{bu} calculation area divisions become smaller and the throttle operation speed increases. When this time is shorter than the time required to calculate K_{bu} , the measurement point moves to a different K_{bu} calculation area before the calculation can be completed. As a result, an occasion to calculate K_{bu} is missed and the accuracy of air fuel ratio correction by K_{bu} drops. This makes it necessary to take into account the air fuel ratio correction accuracy and the occasion for K_{bu} calculations when setting the K_{bu} calculation area divisions. The approach taken to determine the K_{bu} calculation area divisions is described below using Fig. 14.

- The idling area is the area most affected by conditional variations among completed engines and intake air adjustment, so a narrow width is set (Throttle 0 deg - Border 1).
- In the minute throttle-opening range, the required K_{bu} value changes greatly in response to slight changes in the throttle-opening angle as shown in Fig. 13. When a wider division is set in this area, the occasions for K_{bu} calculation increase, but the K_{bu} deviation at the upper and lower boundaries of a single area also increases. This increases the difference in the air fuel ratio within a single area, which reduces drivability.

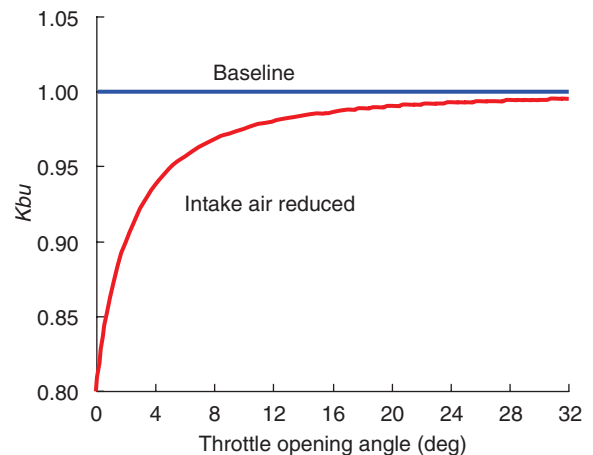


Fig. 13 Change in K_{bu} when amount of intake air is reduced by 20% by bypass

Conversely, setting narrower divisions reduces the effect on drivability within a single area, but the occasions for K_{bu} calculation decrease, so the air fuel ratio correction accuracy drops.

In consideration of these aspects and as a result of investigating the balance between occasions for K_{bu} calculation and drivability, it was confirmed through completed motorcycle tests that both occasions for K_{bu} calculation and drivability can be secured by keeping the

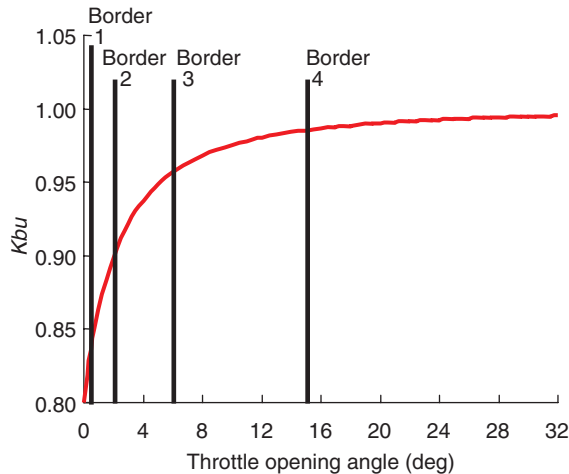


Fig. 14 K_{bu} calculation area divisions

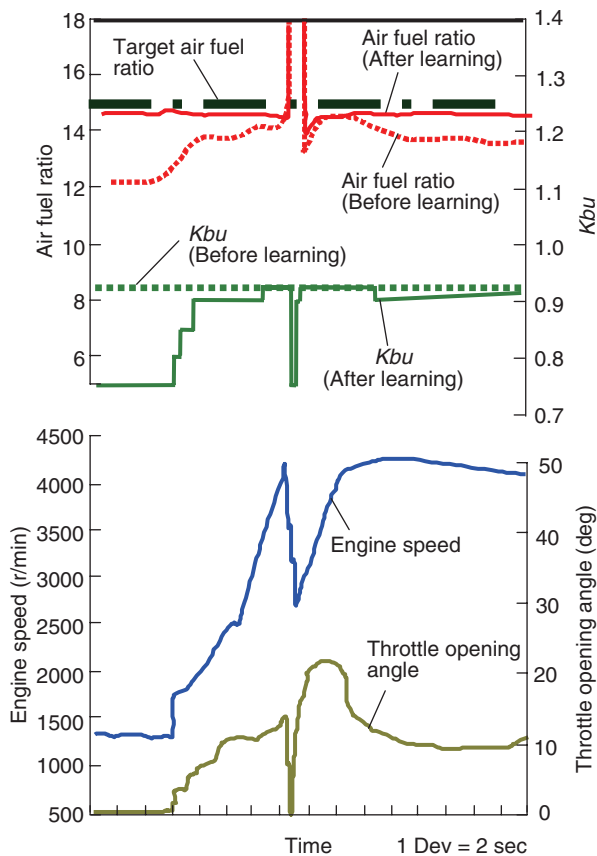


Fig. 15 Effect of K_{bu} calculation division setting on air fuel ratio correction

K_{bu} deviation at the upper and lower boundaries of each area to within 10%. As a result, three K_{bu} calculation areas were set. (Border 1 - Border 4)

- The medium and higher throttle-opening range is relatively unaffected by conditional variations among completed engines, intake air adjustment during idling, and other factors, so a single calculation area was sufficient even in consideration of correction accuracy. (Border 4 - WOT)

Based on the above investigation and confirmation results, five area divisions were determined as shown in Fig. 14.

Figure 15 compares the air fuel ratio correction results for a single K_{bu} calculation area and five K_{bu} calculation areas when O_2 feedback control is inactive. The dotted line shows the air fuel ratio correction results for a single K_{bu} calculation area, and the solid line shows the results when divided into five areas according to the throttle-opening angle. O_2 feedback control is inactive, so K_{bu} is the value calculated under the conditions preceding the test. When performing calculation with a single division, there is only a single K_{bu} value, so there is continued large deviation from the K_{bu} required in response to changes in the throttle-opening angle. This means that correction cannot be performed to the target air fuel ratio. On the other hand, when using five divisions, the five K_{bu} values calculated for the respective divisions prior to the test are applied, so the air fuel ratio is corrected to a value close to the target in response to changes in the throttle-opening angle, even when O_2 feedback control is inactive. This confirmed that the deviation between the target air fuel ratio and actual air fuel ratio can be minimized by setting the minimum necessary number of K_{bu} calculation area divisions in consideration of the change in the amount of intake air when the engine idle speed is adjusted.

7. Maintaining the Engine-Stroke Distinction Function

Next, an alternate method is described of maintaining the engine-stroke distinction function without the intake air pressure sensor, which is the other item mentioned above.

7.1. Conventional Engine-stroke Distinction Method

The conventional system does not have a camshaft position sensor, and distinguishes the engine stroke using the intake air pressure sensor. Figure 16 shows the intake air pressure waveform of a 4-stroke single-cylinder engine in the idling state.

The intake air pressure drops during the intake stroke, and rises gradually to approach atmospheric pressure during the compression, expansion and exhaust strokes. This characteristic is used to distinguish the strokes by measuring the intake air pressure of the intake stroke and the expansion stroke at the same phase. The stroke with the lower air pressure is identified as the intake stroke⁽⁷⁾.

7.2. Stroke Distinction Method Using Crankshaft Rotation Speed Fluctuation

In order to perform stroke distinction without using the intake air pressure sensor, this study focused on the characteristic that the crankshaft rotation speed of a 4-stroke single-cylinder engine becomes slower during the compression stroke.

Figure 17 shows the crankshaft rotation speed fluctuation in the idling state. The crankshaft rotation speed falls during the exhaust, intake and compression strokes, and rises during the expansion stroke. This means that the minimum crankshaft rotation speed occurs during the compression stroke. Therefore, control is performed to

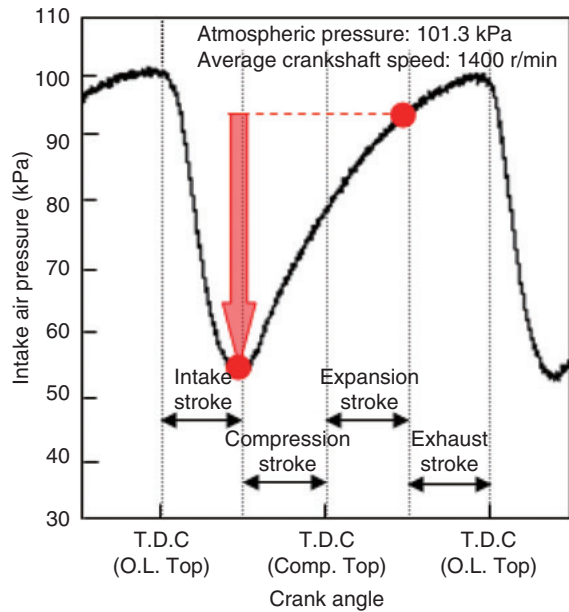


Fig. 16 Variation of intake air pressure at idling speed

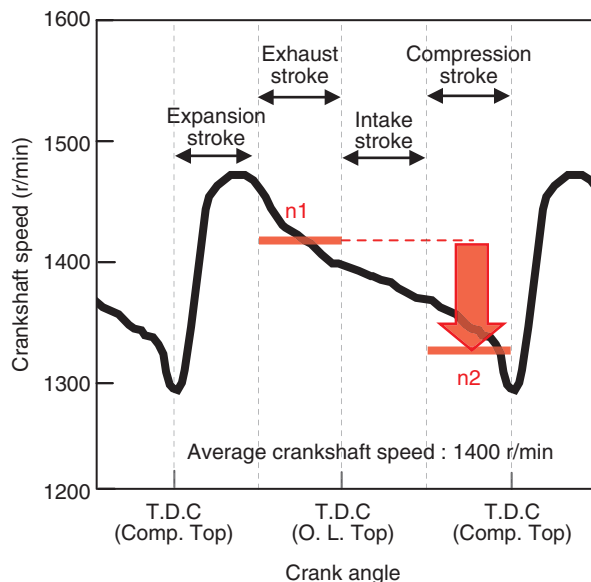


Fig. 17 Variation of crankshaft speed at idling speed

measure the average engine speed during the exhaust stroke n1 and the average engine speed during the compression stroke n2 based on the crank angle sensor signal, and the lower of the two is distinguished as the compression stroke. Note that not including the expansion stroke in the comparison of crankshaft rotation speeds increases resistance to the effects of combustion states such as misfiring.

Figure 18 compares the average engine speeds during the exhaust stroke and the compression stroke, relative to the average engine speed in the idling state. This shows that the average engine speed during the exhaust stroke n1 is always lower than the average engine speed during the compression stroke n2, so stroke distinction is possible even when the idling speed changes. This enabled maintaining the engine-stroke distinction function even without the intake air pressure sensor.

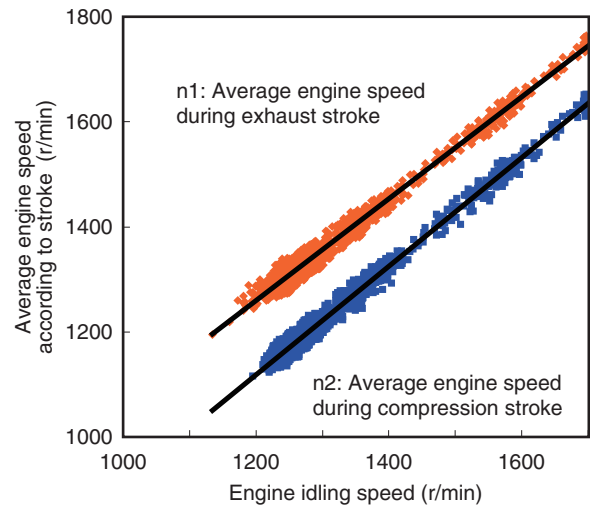


Fig. 18 Comparison of average engine speed between exhaust stroke and compression stroke

8. Results of Confirming Effects

8.1. Exhaust Emissions and Fuel Economy Measurement Results

Table 2 shows the exhaust emissions measurement results, and Table 3 shows the measurement results for mode fuel economy and fuel economy at constant speed. Exhaust emissions and mode fuel economy were measured in Thailand's sixth exhaust emission standards mode, which is a driving pattern equivalent to ECE R40 mode. A motorcycle equipped with the developed system exhibited the same performance for exhaust emissions, mode fuel economy, and fuel economy at constant speed as a motorcycle equipped with the current FI system. This confirmed that a simple system without an intake air pressure sensor can maintain performance equivalent to that of the current system.

Table 2 Comparison of exhaust emissions

	CO (g/km)	THC (g/km)	NOx (g/km)
Current system	0.525	0.217	0.039
Developed system	0.529	0.214	0.038
Regulation values *	2.0	0.8	0.15

* Thailand's sixth exhaust emission standard

Table 3 Comparison of fuel economy performance

	Mode (ECE R40)	Constant speed (50 km/h)
Current system	55.6 km/l	79.6 km/l
Developed system	56.7 km/l	80.0 km/l

9. Conclusion

A simple fuel injection system without an intake air pressure sensor was constructed using new learning control that applies O₂ feedback control and an engine-stroke distinction function based on detection of crankshaft rotation speed fluctuation. The following results were obtained.

- (1) O₂ feedback control enabled accurate measurement of the amount of intake air, which was an issue when eliminating the intake air pressure sensor.
- (2) Performing correction using the operational condition correction coefficient K_{bu} calculated beforehand when O₂ feedback control is active enabled accurate measurement of the amount of intake air even when O₂ feedback control is inactive. In addition, dividing the K_{bu} calculation area into five areas enabled precise correction of the air fuel ratio even when the engine idle speed was adjusted.
- (3) The engine stroke distinction could be maintained by comparing the average engine speed during the compression stroke and the average engine speed during the exhaust stroke.
- (4) The developed system maintained the same performance for exhaust emissions and fuel economy as the conventional system.

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