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Engine Control System using Fuzzy Reasoning

● **Akira Ito** ● **Hirofumi Higashida** ● **Kiyoshi Yagi**
● **Masahiro Tokutsu**

In recent years, fuzzy technology has been adopted in a wide range of consumer, automotive, and industrial electronics products.
At the same time, research in the automotive electronics field has focused on improving fuel economy, decreasing exhaust emissions, and the development of safety features.
While the complexity of recent microcomputer control systems necessitates a large memory capacity, much attention has been directed toward the development of control systems requiring less memory capacity, an important factor in cost reduction.
To solve this problem, Fujitsu Ten has developed a fuzzy engine control system which has shown very favorable results.
This paper explains the structure of the control system, the method of evaluation, and the results obtained.

1. Introduction

The introduction of automobile exhaust restrictions in the latter half of the 1970s has led to the development of new automobile control systems. Among these are engine control systems for improved fuel economy and decreased exhaust emissions, and those designed to provide increased safety and comfort.

In line with these trends, Fujitsu Ten began to explore the increasingly popular fuzzy technology for application to engine control systems, notably for idle speed control (ISC).

ISC ensures that an idling engine runs at the target engine speed previously stored in the memory of a microcomputer. ISC has two aims. First, it aims at making the engine maintenance-free. This is achieved by detecting changes in idle speed due to aging and rotational fluctuations due to load, and then adjusting the engine to the target speed. Second, it aims to reduce fuel costs by maintaining a low target speed.

Most current methods of achieving these aims rely on integral control, which determines the intake air flow according to the deviation between the target and actual engine speeds. However, such methods require a great many design and labor hours for the system to be compatible with both the vehicle and the engine. Another problem is that, since the gains of control constants are at rather low values because of emphasis on stable engine speed, convergence to the target engine speed is slow.

Fujitsu Ten therefore looked into using fuzzy control to overcome these problems and improve control performance.

2. IDLE speed control (ISC)

2.1 Overview of existing ISC

Figure 1 shows the overall system configuration of an ISC system. Figure 2 is a block diagram of the ISC system, and Table 1 lists the functions of each sensor.

The engine control computer calculates a suitable target engine speed based on signals received from the sensors. It then outputs a signal to the ISC valve and controls the air flow through the bypass valve so that the valve opens only as much as is required to achieve the target engine speed. This method of control also varies with the condition of the engine, and the Engine Control Unit (ECU) must select the most suitable form of control.

Some features of ISC are explained below.

1) Starting and warmup control

When the engine is started and for a fixed period afterward, the intake air flow is set at a high level for better startability and running stability.

To shorten the time required for warmup, the air flow is also varied at this time according to the temperature of the coolant.

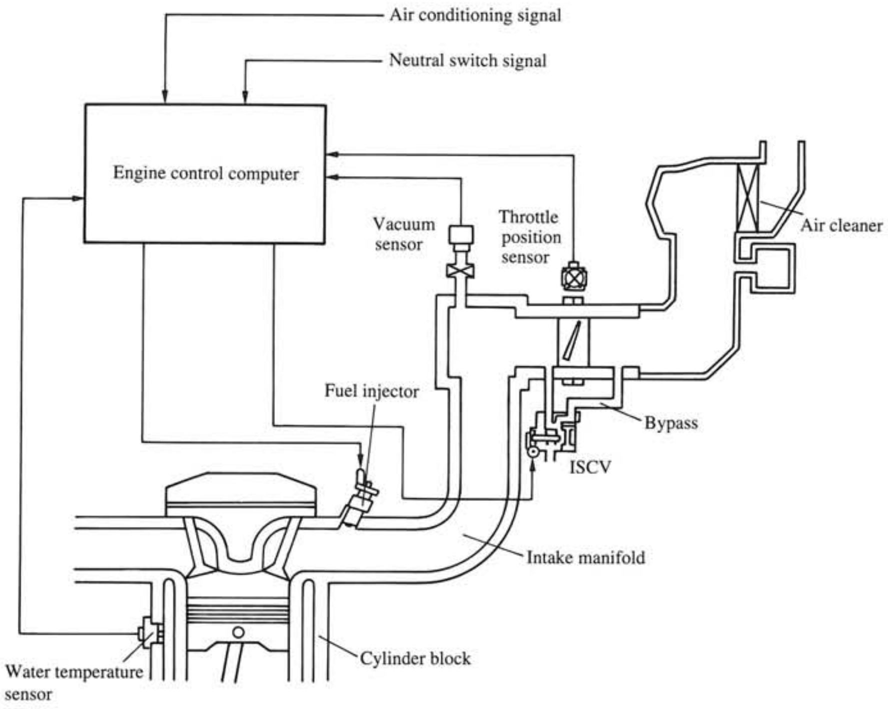


Figure 1. ISC system configuration

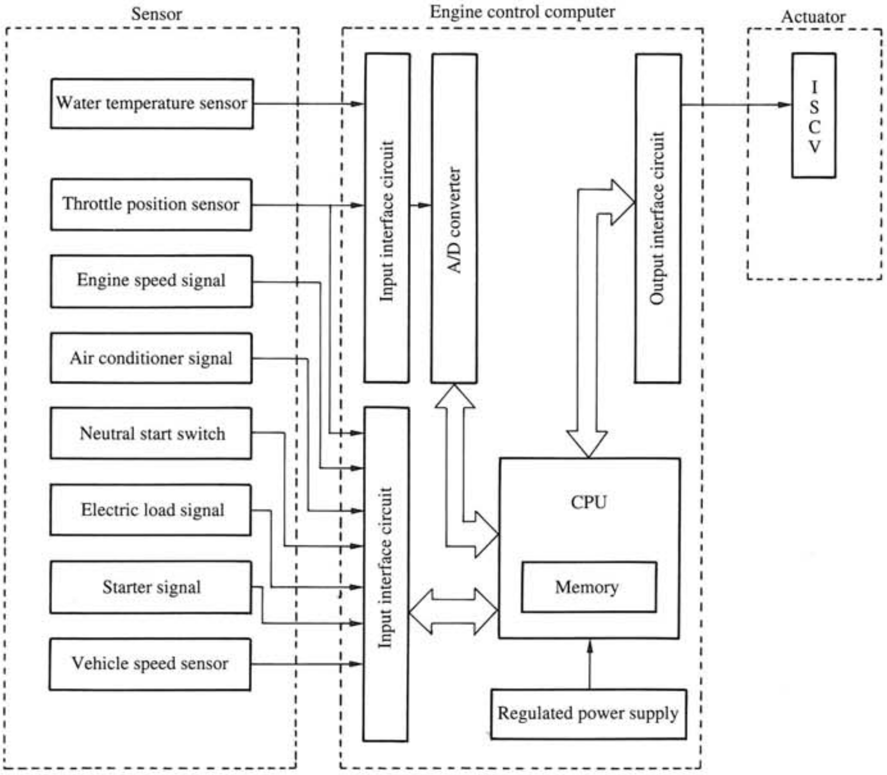


Figure 2. ISC block diagram

Table 1. Peripherals of the ISC system and their functions

Device		Function
Sensors	Engine speed sensor	Detects the engine speed
	Throttle position sensor	Detects a fully-closed throttle
	Water temperature sensor	Detects the temparature of the engine coolant
	Starter signal	Detects operation of the starter
	Air conditioning switch	Detects operation of the air conditioner
	Speed sensor	Detects vehicle speed
	Neutral starter switch (for automatic transmission vehicles)	Detects the position of the transmission shift lever
	Electric load signal	Detects electric load
Actuator		Controls the air flow through the throttle bypass valve
Engine control computer		Determines the target engine speed on the basis of the signals output by the sensors, sends corresponding control signals to the ISCV, and maintains idle speed at the target value

2) Advance control

In vehicles having an automatic transmission, the load on the engine varies each time the shift lever is moved from drive to neutral, or vice versa, and each time the air conditioner is turned on or off. This causes the engine speed to drop or rise. Sudden increases in engine load can result in engine stalling.

When these conditions are detected by means of variations in the signals, the control system changes the opening of the valve according to the anticipated change in the load, thereby suppressing deviations in engine speed.

3) Feedback control of engine speed

When deviation arises between the engine speed and the target engine speed while the throttle valve is fully closed, the control system varies the opening of the ISCV according to the deviation to bring the idle speed closer to the target engine speed. The target engine speed changes when the position of the shift lever is changed or the air conditioner is turned on or off. Table 2 gives an example of changes in the target engine speed.

Table 2. Example of target engine speed (NT)

Transmission and range / Air conditioning	M/T		A/T	
	OFF	ON	OFF	ON
Electric load OFF	650	900	700	900
Electric load ON	750	900	750	900

2.2 Problems with conventional ISC

Figure 3 is a block diagram of existing feedback control of engine speed.

Equation (1) below gives the relationship between factors. The target engine speed is represented by *NT*, the engine speed by *NE*, and the deviation between the target engine speed and the actual engine speed by *E*.

$$E = NT - NE \qquad (1)$$

The amount of control (value of the integral) of the ISCV is represented by IU. This feedback control system

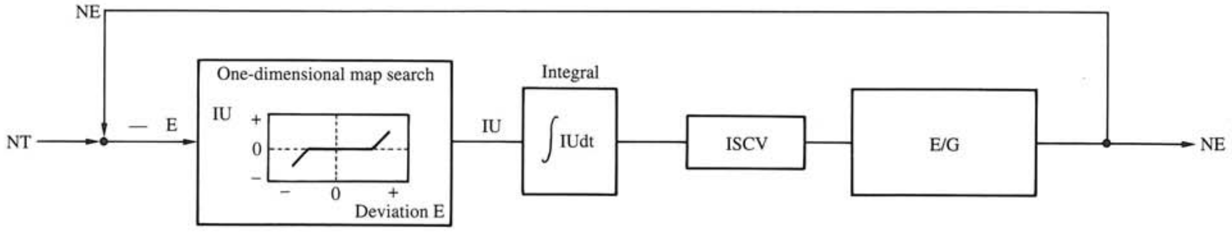


Figure 3. Block diagram of conventional ISC

receives one input and supplies one output. The input is deviation E and the output is IU, the amount of ISCV control. To find IU, the deviation E is calculated and the corresponding value found in the one-dimensional map.

This method of control, however, is difficult in making the control constant suitable for all types of engines in all conditions. Further, from the standpoint of engine speed stability, the gain of the feedback constant is kept rather low and the range of feedback is limited. These conditions lead to the following problems:

① The control constant must be matched to the type of vehicle and engine. This adjustment requires considerable design time.

② Since feedback control is a form of proportional-plus-integral control (PI), the control constant gain must be set at a low level to ensure that the engine remains stable even during changes in its condition (that is, to prevent hunting in the engine speed). Therefore, when the condition of the engine changes, the convergence (follow-up characteristic) of the actual engine speed to the target engine speed is poor.

2.3 Application of fuzzy control

To solve these problems, Fujitsu Ten studied application of fuzzy technology to engine speed feedback control. Fuzzy control is a general purpose control method which can be used for any type of vehicle and engine, and it responds flexibly to changes in the condition of the engine.

Fuzzy control has recently received much attention. In essence, this control system provides what is called equivocal control, that is, very precise control which responds to the purpose of the engine and occasional changes in its condition on the basis of human-language oriented control rules — rules themselves based on human and machine interaction.

3. Fuzzy ISC

3.1 Overview of fuzzy ISC

Figure 4 is a block diagram of engine speed feedback control incorporating fuzzy control (fuzzy ISC).

The deviation is found from the equation below. The target engine speed is represented by *NT*, the engine speed by *NE*, the deviation between the target engine speed and the engine speed by *E*, and the temporal change in the engine speed by *DE*.

$$DE = [NE(i) - NE(i-1)]/\Delta T \qquad (2)$$

The derivative, which is a part of the amount of ISCV control, is represented by DU and the integral, which is another part, by IU. Feedback control of the engine speed involves the following two control systems:

① One input (deviation E) to one output (integral IU), and

② Two inputs (deviation E and DE [temporal change in NE]) to one output (derivative DU).

The sum of the integral IU and the derivative DU is the amount of ISCV control.

To obtain the output, the two control systems use

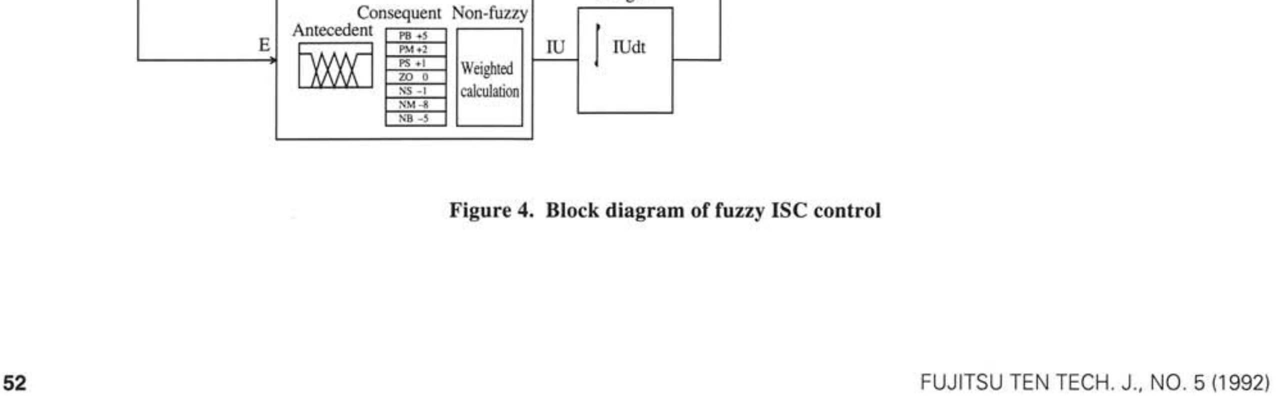


Figure 4. Block diagram of fuzzy ISC control

simplified fuzzy reasoning which defines the consequent as a constant.

The following section briefly explains the method of reasoning.

3.2 Membership function (equivocal set)

The membership function continuously expresses the degree (fast, slow, large, small) of control measures. For example, in response to the input "large," this function expresses numerically how large (in terms of the human expressions very large and quite large), and is often represented by a triangle, trapezoid, or bell. To make the system easier to control, Fujitsu Ten's fuzzy ISC uses only a triangle and a trapezoid, since the triangle and the bell serve the same purpose in control action.

Figure 5 shows the membership functions used in fuzzy ISC control.

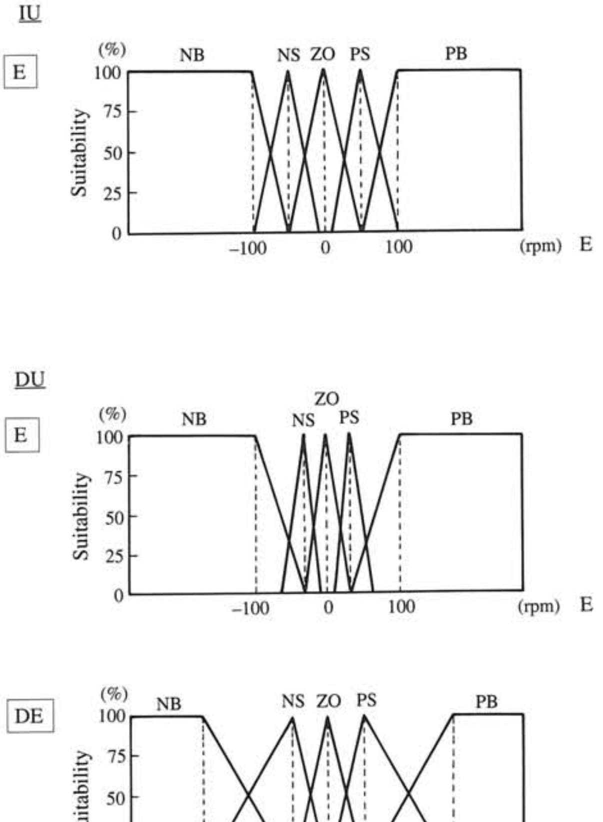


Figure 5. Membership function (IU rule, DU rule)

3.3 Control rules

Control rules are a set of predetermined rules which find the required output from the obtained input according to a membership function. For example, the response to the input "the undershoot in the engine speed is very large" is "make the opening of the ISCV very large."

There are two types of fuzzy ISC control rules, one set for the integral (IU) and one for the derivative (DU).

Figure 6 shows the integral (IU) control rules. The control rules have five consequents (outputs) for five membership functions of deviation E which represent the antecedents (inputs).

Figure 7 shows the control rules for the derivative (DU).

The antecedent (input) is shown as a two-dimensional map which comprises the membership function for the temporal change DE of the engine speed NE.

Additional rules have been added for the consequent (output). Rules 1 to 9 are standard rules which fix either E or DE at ZO (ZERO) and rules 10 to 13 are added to shorten the time required to achieve stability of the engine speed when the engine speed has neared the target engine speed. Further, rules 14 to 17 have been added to control undershoot and improve the engine's resistance to stalling. Rules 18 to 21 have been added to control overshoot. This brings the total number of rules to 21.

For example, rule 1 indicates that "if DE is large and E is zero, move DU a little."

In this rule, the input is the variation DE between the deviation E and NE. In other words, "If the input is far from the target engine speed, or the undershoot of NE is large, control for a great move is required." This is the basic rule of feedback control, but rule 22, explained below, has been added to fuzzy ISC.

Rule	Antecedent	Consequent
1	If E is PB,	Set IU to PB.
2	If E is PS,	Set IU to PS.
3	If E is ZO,	Set IU to ZO.
4	If E is NS,	Set IU to NS.
5	If E is NB,	Set IU to NS.

Figure 6. Control rules for IU

When a large drop in NE is detected, the control system naturally opens the valve more so that the air flow through the bypass increases. However, since there is a

DE \ E	PB	PS	ZO	NS	NB
PB	⑭ PB	⑮ PB	① PB	⑫ PB	⑱ PM
PS		⑯ PM	② PM	⑬ PS	⑲ ZO
ZO	⑥ PS	⑦ PS	③ ZO	⑧ NS	⑨ NS
NS	⑰ ZO	⑩ NS	④ NS	⑳ NS	
NB		⑪ NS	⑤ NM	㉑ NM	

The circled numbers in the chart above indicate the rule number. The vertical and horizontal axes represent the antecedent, and the data in the chart is the consequent. Abbreviations are explained below.

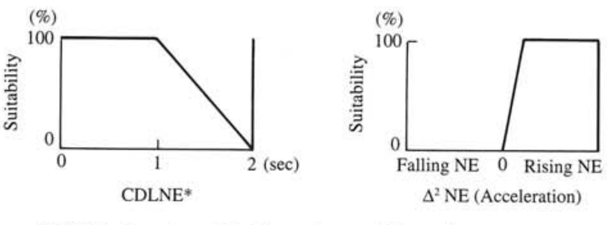
NB: NEGATIVE BIG
NM: NEGATIVE MEDIUM
NS: NEGATIVE SMALL
PB: POSITIVE BIG
PM: POSITIVE MEDIUM
PS: POSITIVE SMALL
ZO: ZERO

Figure 7. Control rules for DU

control lag, NE temporarily overshoots the target engine speed. Since NE is rising at this time, the control system narrows the bypass and NE undershoots the target speed. Hence hunting occurs several times before the actual engine speed finally converges to the target engine speed. Rule 22 was added to solve this problem. This rule determines a period of time starting from the point when DE (variation of NE) exceeds a certain value and creates a membership function according to the second-order derivative. When the control system detects a rise in NE after it has fallen, it lowers the amount of control to suppress overshoot.

Adding rule 22 greatly improves the convergence of NE. Figure 8 shows the membership function, Fig. 9 shows rule 22 and Fig. 10 compares control performance before and after rule 22 is added.

Rule 22 is only effective when certain conditions have been established. It is not a simple supplementary control scheme as is conventional control. Since it converts the results of inference by both the basic rules and rule 22 into output by way of weighting (explained below), it yields very smooth outputs. It is therefore a preeminent part of fuzzy control.



*CDLNE: A counter which clears whenever DE exceeds a certain value and increments for a certain fixed period of time.

Figure 8. Membership function of rule 22

Antecedent	Consequent
When CDLNE ≤ 2 (sec) and Δ^2 NE is rising	NVB

NVB: NEGATIVE VERY BIG

Figure 9. Control rules (rule 22)

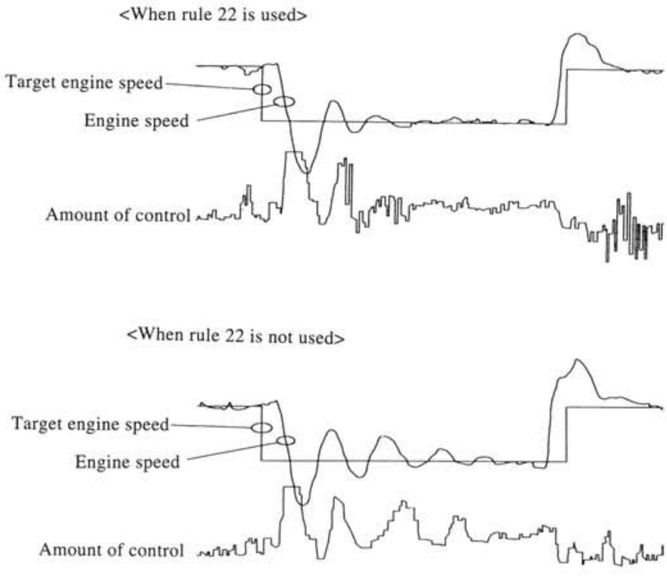


Figure 10. Results of control with and without rule 22

3.4 Non-fuzzy constants

Fuzzy inference generally defines the consequent of the control rule using the membership function. However, since Fujitsu Ten's new control system is designed to be installed in a vehicle, it is beneficial if the program size can be reduced and the processing speed enhanced. Therefore, fuzzy inference in Fujitsu Ten's new control system defines the consequent as a constant. Figure 11 shows the non-fuzzy constants for integral control IU and derivative control DU.

Non-fuzzy calculation is shown in the equation below. Weighted calculation is performed on the suitability obtained using the membership function in relation to the consequent obtained using the control rule.

<Non-fuzzy constants of IU consequent>

PB	+0.6	(%)
PS	+0.3	
ZO	0.0	
NS	–0.15	
NB	–0.3	

<Non-fuzzy constants of DU consequent>

PB	+7.0	(%)
PM	+4.0	
PS	+1.0	
ZO	0.0	
NS	–1.0	
NM	–3.0	
NB	–7.0	

Figure 11. Non-fuzzy constants of IU and DU

$$\text{Consequent (output)} = \frac{\sum_{n=1}^{n}(\text{Consequent of rule 1} \times \text{Suitability of rule 1})}{\sum_{k=1}^{n}(\text{Suitability of rule 1})} + \frac{\sum_{k=2}^{n}(\text{Consequent of rule 2} \times \text{Suitability of rule 2})}{\sum_{k=2}^{n}(\text{Suitability of rule 2})} + \frac{\sum_{k=n}^{n}(\text{Consequent of rule n} \times \text{Suitability of rule n})}{\sum_{k=n}^{n}(\text{Suitability of rule n})} \quad \text{................(3)}$$

Figures 12 and 13 show the numerical relationship between the input and output of the integral and derivative based on the membership functions and control rules.

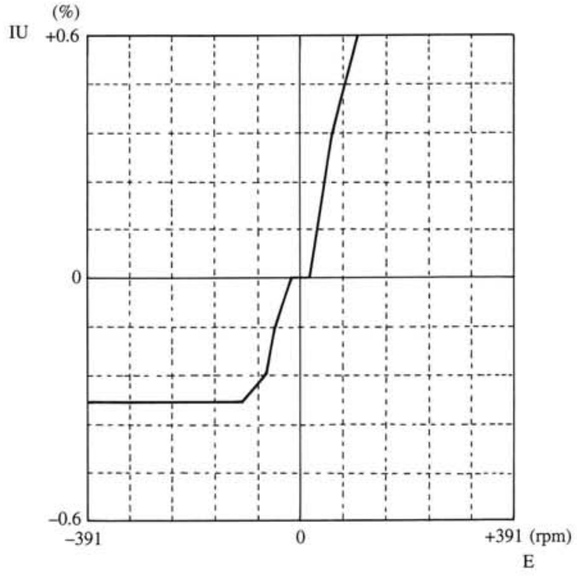


Figure 12. Relationship between input and output of integral IU

Note that rule 22 has not been applied in Figure 13.

The relationship between the input and output of the integral in fuzzy ISC (Fig. 4) is represented by a two-dimensional graph from a single input (antecedent). The relationship between the input and output of the derivative is represented by a three-dimensional graph from two inputs (antecedents). It is clear that there is a complex input/output relationship between inputs E and DE and output DU (derivative).

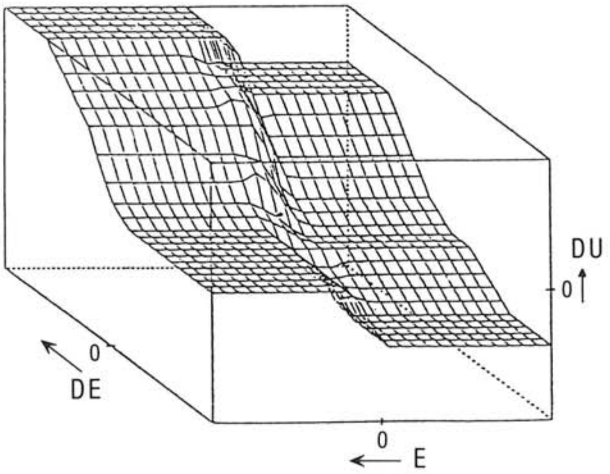


Figure 13. Relationship between input and output of derivative DU

4. Result of evaluation

We evaluated control performance (particularly convergence) and stability against disturbance for both the conventional engine speed feedback control system (conventional ISC) and the new engine speed feedback control system using fuzzy control (fuzzy ISC).

4.1 Control performance (Convergence)

To evaluate control performance, we observed convergence of the engine speed immediately after load on the engine was increased and immediately after it was removed, since these two conditions pose the greatest difficulty for an ISC system.

Figure 14 shows the relationship between the conventional and fuzzy ISC schemes in undershoot immediately after load is added while the engine is idling. The diagram clearly indicates that there is no significant difference between the undershoot under conventional ISC and that under fuzzy ISC when a change in the load can be predicted

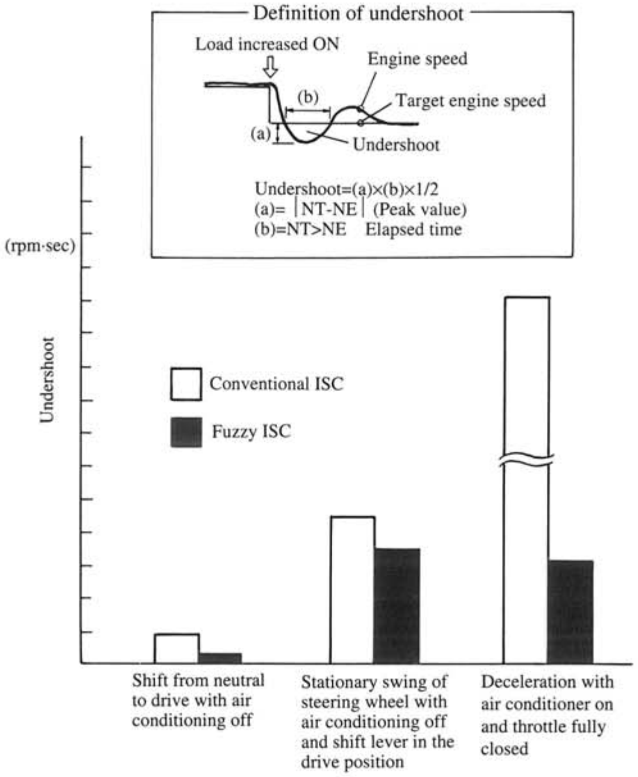


Figure 14. Undershoot of ISC (load increased)

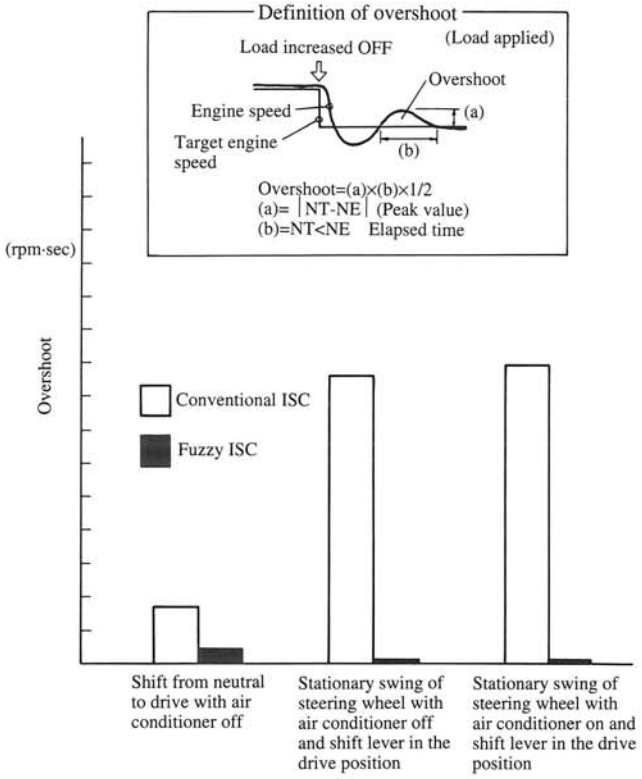


Figure 15. Overshoot of ISC (load increased)

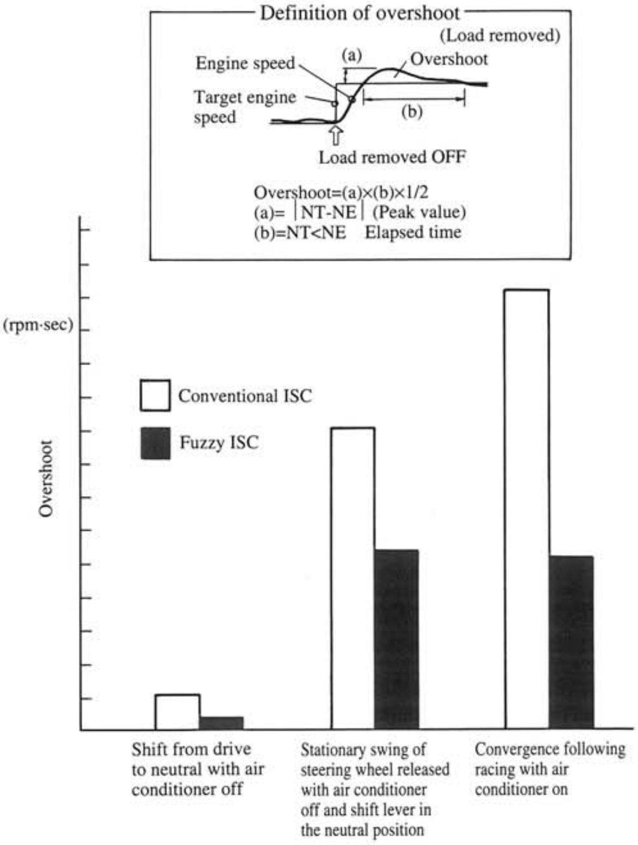


Figure 16. Overshoot of ISC (load removed)

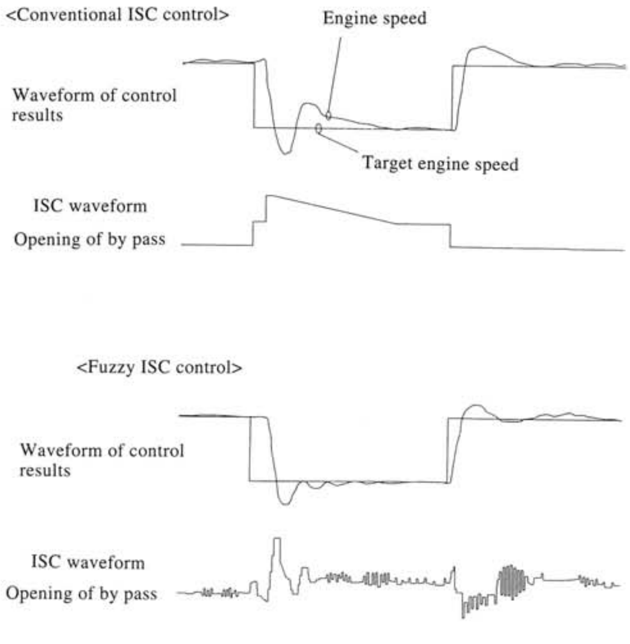


Figure 17. Waveforms of control signal and results of ISC control

from input signals (the computer recognizes the condition of the air conditioner and position of the shift lever from inputs). This is accounted for by the fact that conventional ISC systems are also capable of detecting some load fluctuations through adaptive advance control. However, this form of control has a drawback in that it cannot easily predict the load on the engine when, for example, acceleration is reduced from the maximum level to a lower level (at which time the computer considers the engine to be idling). Undershoot is greatly reduced when fuzzy ISC is used.

Figure 15 shows the relationship between conventional ISC and fuzzy ISC in overshoot immediately after load is added while the engine is idling. The diagram shows that fuzzy ISC greatly reduces overshoot in comparison with conventional ISC.

Figure 16 shows the relationship between conventional ISC and fuzzy ISC in overshoot immediately after load is removed while the engine is idling. As is evident from the diagram, there is much less overshoot following a decrease in the load when fuzzy ISC is used than when conventional ISC is used.

The above results showed that fuzzy ISC provides superb control performance (convergence) when compared with conventional ISC.

Figure 17 shows the actual engine speed and engine motion for both conventional ISC and fuzzy ISC.

4.2 Stability against disturbances

To evaluate stability against disturbances, we recreated disturbances by intentionally making the air-fuel ratio high to reduce the torque generated by the engine, and measured the fluctuations (hunting width) of the engine speed. We judged that the smaller the deviation in the engine speed when a disturbance is exerted (lean fuel), the stabler the engine speed.

Figure 18 shows the relationship between the hunting width of the engine speed when the engine is subjected to the above disturbance for each type of control (conventional ISC and fuzzy ISC).

As can be seen in the diagram, the hunting width of the engine speed during disturbance up to a certain air-fuel ratio is the same for both conventional ISC and fuzzy ISC. However, as the fuel is made leaner, the hunting width of the engine speed under fuzzy ISC increases more slowly than under conventional ISC.

We therefore confirmed that fuzzy ISC provides better stability against disturbance than conventional ISC.

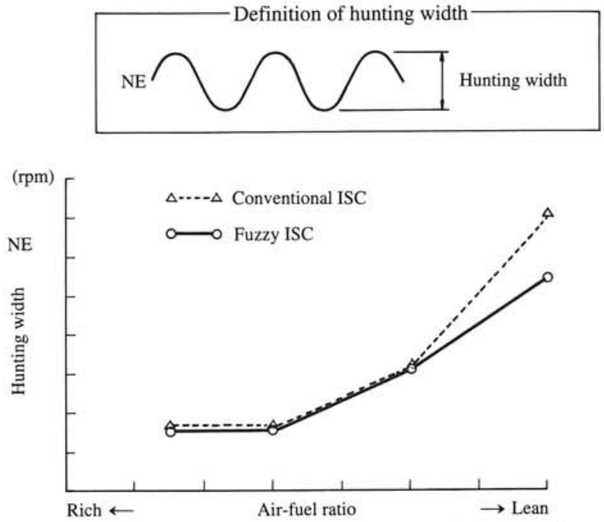


Figure 18. Relationship between air-fuel ratio and hunting width of engine speed with ISC control

5. Conclusion

As a result of our study on the application of fuzzy control to engine speed feedback control for an idle speed control system, we succeeded in improving control performance over the conventional method of engine speed feedback control.

The use of control algorithms based on human-language expressions, a characteristic of fuzzy control, promises to achieve a reduction in design time required for matching, a process which has been a major problem in designing conventional control systems.

The evaluation covered in this paper focuses mainly on performance, but much work still needs to be directed toward the memory capacity required for software before fuzzy ISC can be made practical. To this end, in addition to our study on fuzzy ISC, we are also currently looking into a method of storing results obtained using fuzzy inference into memory as constants.

This method would eliminate the need for a logic program in the inference section, reduce memory capacity requirements, and shorten execution time.

Though perhaps not apparent from the brief explanation of fuzzy ISC provided in this paper, we can say that we succeeded in improving the performance of the control system without changing any part of the hardware used in a conventional system.

This first attempt at applying fuzzy control to engine control, though restricted to ISC, showed very promising results. We therefore plan to continue experiments in this field, applying fuzzy control to other types of engine control systems.

Akira Ito

Employed by the company since 1985. Engaged in development and quality control for the electronic equipment for automobiles. Currently in the System Research and Development Department, Vehicle Electronics Division.

Kiyoshi Yagi

Employed by the company since 1977. Engaged in developing electronic equipment for automobiles. Currently in the System Research and Development Department, Vehicle Electronics Division.

Hirofumi Higashida

Employed by the company since 1984. Engaged in developing electronic equipment for automobiles. Currently in the System Research and Development Department, Vehicle Electronics Division.

Masahiro Tokutsu

Employed by the company since 1986. Engaged in developing electronic equipment for automobiles. Currently in the System Research and Development Department, Vehicle Electronics Division.