

Development of Highly Functional ECU for Next Generation of Inline-four Engines

Makoto MURAKAMI*

Tatsuo YAMANAKA*

Yasumasa KAITANI*

ABSTRACT

We developed an engine control unit having a new functional composition, with the goal of applying it to the next generation of direct-injection engines, port-injection engines, and hybrid electric vehicle engines. To achieve these functions, the heat generated by the components and the number of parts were reduced. As a result, we decreased generated heat and reduced the number of parts by 30% compared to the conventional engine control unit.

Also, in order to reduce the minimum injection quantity in direct-injection engines, feedback control was performed by detecting the close timing of the injector, and we reduced the minimum value of the injector drive signal time by 46% compared to the conventional system.

1. Introduction

When considering the variations of power train systems, the conventional combinations of the engine and transmission were limited, as Fig. 1 shows. As a result, the combinations of engine control unit (ECU) and transmission control unit (TCU), as well as the functions they required were also limited. To address this, there are past examples of ECUs and TCUs being integrated and developed as a single unit. However, due to environmental regulations that have continued to become more stringent in recent years, the functions required for the engine and transmission have also increased as shown in Fig. 2. As these functions increase, it has become difficult to integrate the ECU and TCU, so they must now be developed separately from one another. In terms of engines, the use of direct-injection engines has expanded, as these offer

superior fuel consumption. Also, the size of the engine is being further reduced through the use of supercharged mechanisms⁽¹⁾. As Fig. 3 shows, in order to achieve these new functions, there are more types of devices associated with the engine, which leads to a higher number of parts composing the ECU and an increase in the heat that is generated from parts. Also, a new algorithm to control devices has become necessary⁽²⁾. Meanwhile, it is necessary to minimize cost and size, while dealing with the increase in functions. Therefore, we developed a highly functional ECU capable of being used in the next generation of direct-injection engines, port-injection engines, and hybrid electric vehicle (HEV) engines.

This paper introduces example applications of function

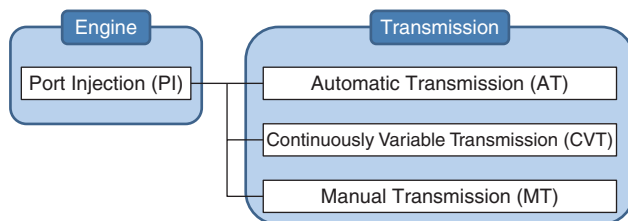


Fig. 1 Power train variations

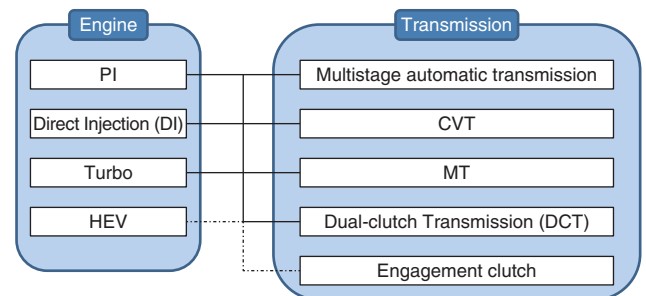


Fig. 2 Diversification of power train variations

* Automobile R&D Center

integration technology for establishing a highly functional ECU and technology for decreasing the ECU circuit-generated heat that increases as the number of devices increase.

Also, CO₂ emissions regulations and fuel consumption regulations for vehicles are becoming more stringent, and regulations on gas emissions are expected to become stricter throughout the world in the future⁽³⁾. In Europe, the new law EURO6 is scheduled to go into effect beginning in 2014. For direct-injection engines in particular, multi-stage injection will be required in order to decrease particulate matter (PM)⁽⁴⁾. Multi-stage injection is known to help reduce PM by enhancing the homogeneity of the air-fuel mixture and suppressing the adhesion of fuel to the surface of the internal wall of the cylinder. For multi-stage injection, it is necessary to reduce the minimum injection quantity by decreasing the minimum usable value (MinTi) of the injector drive signal time (Ti). As an effective means of decreasing this MinTi, we introduce technology that detects and corrects the close timing of the injector.

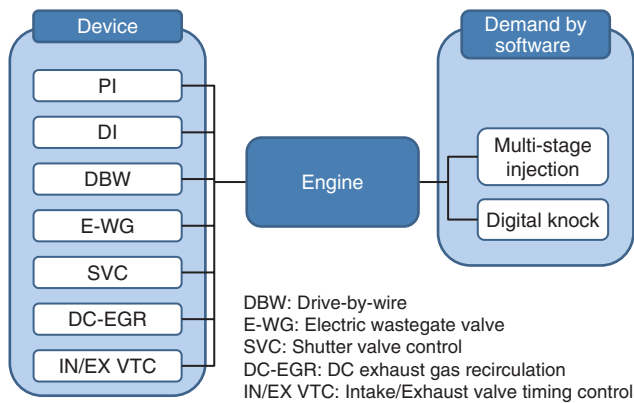


Fig. 3 Engine device and demand by software

2. Development Goals

As mentioned earlier, devices and software are increasing as functions for enabling technology required to address environmental regulations increase. Table 1 shows the relationship between this technology and devices/software. Also, when engines for HEVs are assumed in addition to direct-injection engines and supercharged mechanisms, the number of circuit components for the ECU grows, leading to the concern that heat generated by the circuitry will also increase.

As far as the rising number of part indicates, the circuit components are reduced by using integrated driver ICs and a buck-boost power supply to revise circuits that operate at low voltage and by using microcomputer functions to simplify peripheral circuits.

Table 1 Engine technology

Technology	Device and software
Lean-burn engine technology Engine with supercharger technology Downsizing engine technology	E-WG DC-EGR
Atkinson cycle technology	IN/EX VTC
PM reduction technology	Multi-stage injection Dual injection
Knock detection technology	Digital knock filter

Also, the heat generated by circuits in direct-injection ECUs is higher than in port-injection ECUs. Therefore, heat-radiating structures are becoming more complex and the structural weight is increasing. In order to decrease this structural weight, the actual heat generated by the injector drive circuit was reduced, and heat-radiating structures were simplified.

In terms of software development, we placed a focus on multi-stage injection, which is effective at decreasing the PM of direct-injection engines. Technology that detects and corrects the injector close timing is effective at decreasing the MinTi per injection, and we confirmed the feasibility of that technology.

Our goals are summarized below:

- (1) Part integration to achieve functions that assume applications in various engine types.
- (2) In terms of direct-injection injector control: the reduction of heat generated by drive circuits and creating a means of reducing MinTi.

3. Part Integration to Achieve Functions

The ECU that we developed can be applied to the engine types shown in Fig. 4, and this ECU has approximately 200 functions. We introduce technology that was utilized to achieve these functions.

We performed the required analysis for approximately 200 functions of each type of engine to be controlled by the ECU, and we clarified the control functions that were

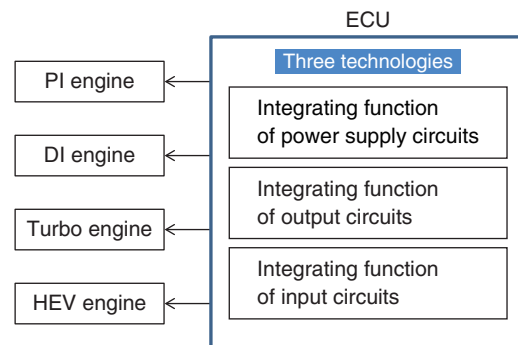


Fig. 4 Application of highly functional ECU

common to each type of engine as well as those that were separate. Based on this, we predicted the processing load and required substrate surface area, selected the size of the central processing unit (CPU), and established target values for substrate size and case size.

We introduce the following three types of technologies shown in Fig. 4 that are used to install the approximate 200 functions: technology that integrates the power supply components, technology that integrates output function parts, and technology that integrates input function parts.

3.1. Integration of Power Supply Components

We utilized a system power supply IC in generating the power supply for the ECU that we developed. In addition to offering the functions of the conventional power supply IC, the system power supply IC also provides CAN, LIN and other communication functions, external hardware input functions, etc. Also, the conventional ECU required a circuit for stabilizing the supplied voltage when the battery voltage varied. However, the new system power supply IC that we developed has a buck-boost function that did not exist in previous power supply ICs, and this function can stabilize the supplied voltage during battery voltage variations. Therefore, we were able to reduce the amount of the conventional circuitry. Figure 5 shows the composition of the system power supply IC that we utilized.

3.2. Integration of Output Function Parts

Most of the circuits for achieving the output functions of the ECU that we developed have been integrated into a semiconductor. In the past there had been the idea of integrating circuits into a semiconductor, and function integration began to move forward. However, the functions that could be integrated were limited, because doing so concentrated generated heat. Due to advances in semiconductor processes in recent years, however, the level of integration was increased and internal resistance was improved, enabling a reduction in generated heat loss and

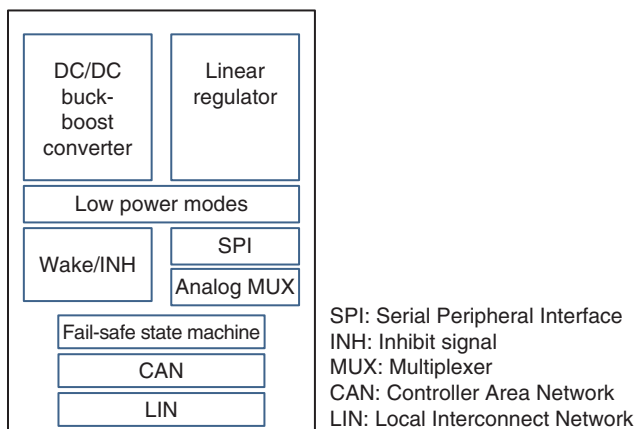


Fig. 5 System power supply IC

more function integration than was previously possible. Figure 6 shows an example of how the output driver IC was integrated. This integration made it possible to simplify the circuitry and reduce the number of parts.

3.3. Integration of Input Function Parts

An example of the reduction of input function parts is the application of the digital knock filter. First, Fig. 7 shows the relationship between the frequency band of the signal required for detecting knocking and the analog digital converter (ADC) sampling frequency. In the conventional CPU, ADC sampling frequency was approximately 100 kHz, close to the frequency band required for detecting knocking, so the use of a high-order analog filter was required. This made the circuit composition complicated and increased the number of parts.

However, as CPUs advanced, ADCs also became capable of high-speed sampling. In the CPU used in the ECU that we developed, sampling was possible at a frequency of approximately 1000 kHz, which was separated at a distance from the frequency band required for knocking, and it became possible to use low-order analog filters. This was how the analog filter composition was simplified and the number of parts reduced.

As described above, integrating the power supply components, output function parts, and input function parts made it possible to reduce the number of parts by 30% over that of the conventional ECU.

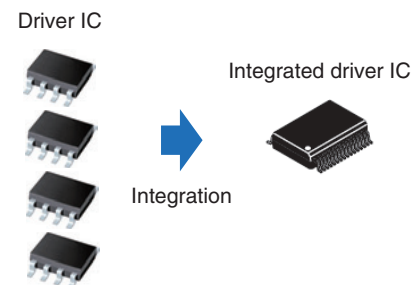


Fig. 6 Integrated driver IC

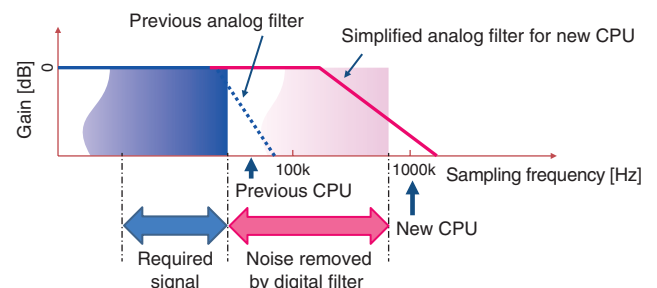


Fig. 7 Analog filter characteristics

4. Direct-injection Injector Drive Circuit

4.1. Reducing Generated Heat

To comply with EURO6, it was necessary to divide the fuel injection quantity that had conventionally been injected only once into multiple stages of injections. Delivering multi-stage injection increases the number of times that the direct-injection injector drives, the quantity of power that is output, and the quantity of heat that is generated. To prevent this from occurring, we introduced a means of decreasing the heat generated by the boost power supply of the direct-injection injector drive circuit.

Every time a direct-injection injector drives, it requires a supply of opening energy from the DC/DC boost converter (boost converter) for the drive voltage. Therefore, in order to deliver multiple injections, it is necessary to decrease the heat that is generated by the boost converter, and the quantity of heat increases in proportion to that energy. In order to calculate the quantity of heat generated by the boost converter, we utilized circuit simulation and optimized the drive circuit composition and components and the switching frequency.

Figure 8 shows an overall diagram of the boost converter utilized in the ECU. The direct-injection injector drive voltage is generated by boosting the input battery voltage. Also, Fig. 9 shows the relationship between the switching frequency and the quantity of heat generated by each element of the boost converter, by providing simulation results and true measurement results for each. Figure 9 shows that when the switching frequency increases, the quantity of heat generated by the inductor decreases, while the heat generated by the semiconductor parts (diodes, FETs) increases. Therefore, a frequency at which the total quantity of heat generated by the entire boost converter is at a minimum can be detected. By utilizing this frequency, the quantity of heat generated by the boost converter was able to be decreased.

4.2. Direct-injection Injector Close Timing Detection

The region of short-time injection required for multi-stage injection was not able to be used until now, because the injection quantity in relation to the drive signal disperses greatly in this region depending on the individual injectors. Therefore, we attempted to accomplish injection in this

previously unusable region by using the ECU to correct the dispersion.

4.2.1. Injector injection quantity and individual dispersion

The relationship between injection quantity Q and T_i , and the dispersion of Q in individual injectors is shown in Fig. 10. Figure 10 clearly shows that the dispersion increases in the region where T_i is short.

4.2.2. Close-timing detection algorithm

The fundamental concept for detecting close timing is as follows: changes occur in the inductance of the injector coil due to movement of the injector core at the close timing, and the resulting inflection point that occurs in the voltage is detected. We therefore added a circuit to the ECU to detect the voltage of the injector.

By processing the voltage signal obtained by the ECU, the voltage inflection point that occurs as a result of closing is detected and is used as the close timing.

4.2.3. Detection results

In order to check detectability, we compared the actual measured values and detected values of the close timing (T_{off}) of 10 injectors with respect to T_i .

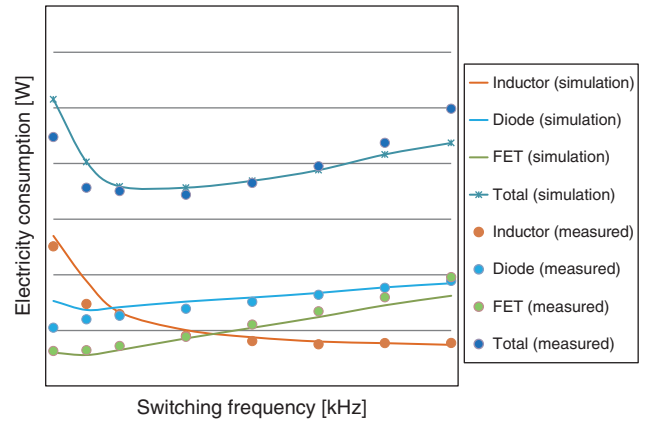


Fig. 9 Relationship between switching frequency and loss of DC/DC boost converter

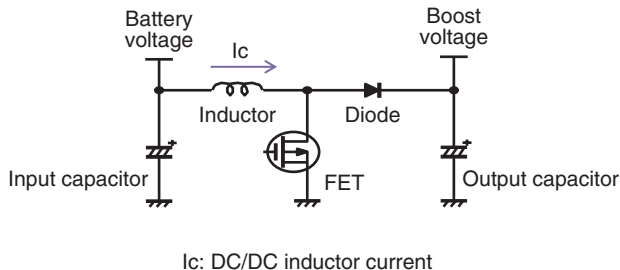


Fig. 8 DC/DC boost converter

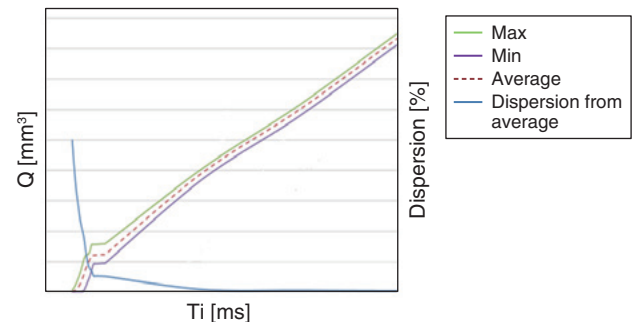


Fig. 10 T_i - Q characteristics

Figure 11 shows a high correlation between the actual measured value and the detected value. As a result, we were able to verify the utility of the close timing detected by the ECU.

4.2.4. Feedback control

Figure 12 shows Ti-Q characteristics when Ti feedback control is performed using the results of the close-timing detection.

Figure 12 also shows a reduction in the dispersion of Q in the region where Ti is short as compared to before control was performed. This control operation was able to decrease MinTi by 46%.

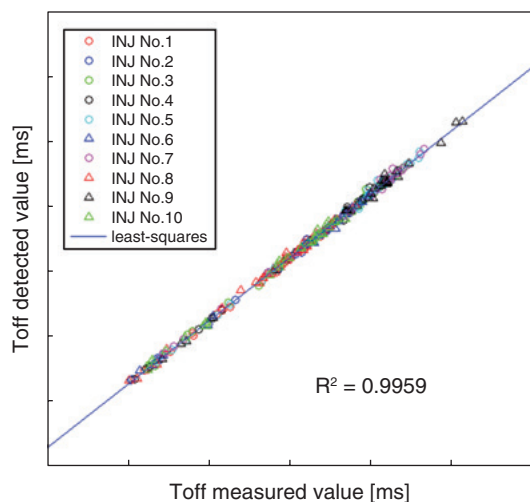


Fig. 11 Comparison of Toff measured value and Toff detected value

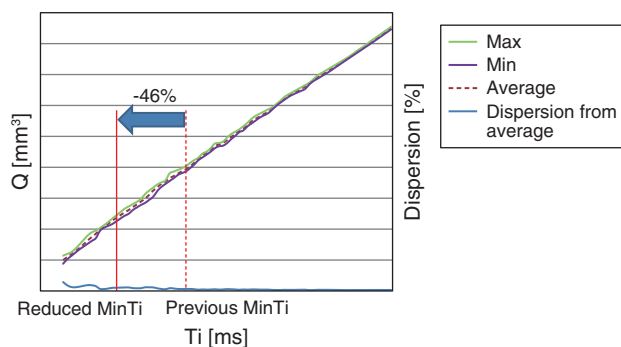


Fig. 12 Ti-Q characteristics after feedback control

5. Conclusion

Amidst the increase in functions for enabling technology required for environmental regulations, we decreased the number of circuit components by utilizing an integrated driver IC, revising low-voltage operation circuits

through the use of a buck-boost power supply, and used microcomputer functions to simplify peripheral circuitry. We also reduced the actual heat generated by the direct-injection injector drive circuit and simplified heat-radiating structures to decrease weight. In addition, we achieved injector control technology that reduces the MinTi in order to enable multi-stage injection of the direct-injection injector that is effective at reducing PM. By developing a highly functional ECU that applies these technologies, we achieved the following results:

- (1) We reduced the number of parts by 30% while assuming applications in future engine types.
- (2) With regard to direct-injection injector control, we reduced the heat generated by the drive circuit, and created a means of reducing the minimum injector drive time value by 46%.

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Author



Makoto MURAKAMI



Tatsuo YAMANAKA



Yasumasa KAITANI