

A Custom Integrated Circuit with On-chip Current-to-Digital Converters for Active Hydraulic Brake System

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ABSTRACT

This paper presents a custom integrated circuit (IC) on which circuit functions necessary for “Active Hydraulic Brake (AHB) system” are integrated, and its key component, “Current-to-Digital Converter” for solenoid current measurement. The AHB system, which realizes a seamless brake feeling for Antilock Brake System (ABS) and Regenerative Brake Cooperative Control of Hybrid Vehicle, and the custom IC are installed in the 4th-generation Prius released in 2015. In the AHB system, as linear solenoid valves are used for hydraulic brake pressure control, high-resolution and high-speed sensing of solenoid current with ripple components due to pulse width modulation (PWM) is one of the key technologies. The proposed current-to-digital converter directly samples the drain-source voltage of the sensing DMOS (double-diffused MOSFET) with an analog-to-digital (A/D) converter (ADC) on the IC, and digitizes it. The conversion characteristic is compensated for the DMOS onresistance variation by an ADC reference compensation technique. A hybrid Active-Passive $\Delta\Sigma$ A/D converter is adopted and realizes small chip area and low power dissipation. A post-processing digital CIC (cascaded integrator-comb) decimation filter removes the ripple components which synchronize with the PWM switching efficiently. Through the design optimization of these, a 12-bit resolution and a response speed necessary for the solenoid current control have been achieved. The IC chip is fabricated in Toyota in-house SOI 0.35 μ m BiCDMOS process.

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INTRODUCTION

In recent brake control systems, electronic control of hydraulic pressure with microcomputers is making progress as represented by ABS (Antilock Brake System), VSC (Vehicle Stability Control system), ECB (Electronically Controlled Brake system), and Regenerative Brake Cooperative Control for HV (Hybrid Vehicle) [1], [2]. Toyota has developed “Active Hydraulic Brake (AHB) system” which realizes a seamless brake feeling for the ABS and the regenerative brake system of HV. This system is installed in the 4th generation Prius released in 2015.

In the AHB system, as linear solenoid valves are used for hydraulic brake pressure control, high-speed and accurate feedback control of the solenoid current is demanded. The solenoid current is controlled using pulse width modulation (PWM) by the combination of a custom IC and an off-chip microcomputer. The sensing of solenoid current with ripple components by PWM is one of the key technologies.

In the conventional solenoid current sensing, the current values are converted to voltage outputs using analog on-resistance compensation circuits with a number of operational amplifiers (opamps) to be digitized by analog-to-digital (A/D) converters (ADCs) of a microcomputer. Also, in addition to external RC filters for anti-aliasing, digital filters with software operation are necessary to sufficiently reduce high-frequency noise including ripple components

with PWM control. For these processes, the circuit scale and the software scale are relatively large, and the performance in resolution, control response, and noise reduction is limited.

Recent advancement in integrated circuits (IC) and signal processing technologies has enabled on-chip integration of high-performance A/D converters and digital filters onto custom ICs. Specifically, $\Delta\Sigma$ A/D converters are used in a variety of applications as a high-resolution ADC architecture [3], [4]. The scale of analog circuits is relatively small, and by designing a $\Delta\Sigma$ modulator circuit topology and a post-processing digital filter properly, the resolution, response speed, and noise reduction can be optimized depending on system requirements.

This paper presents a custom IC on which circuit functions necessary for the AHB system are integrated, and its key component, “Current-to-Digital Converter” for solenoid current measurement. First, the Toyota AHB system in 4th-generation Prius and solenoid current sensing requirement are introduced. Next, the custom IC we have developed and its functions are presented. Then, after a conventional current sensing circuit using an analog compensation technique is discussed, the proposed current-to-digital converter with a $\Delta\Sigma$ ADC technology, including on-resistance compensation, hybrid Active-Passive $\Delta\Sigma$ modulator, and post-processing digital filter, is presented. Lastly, the design and experimental results of the chip are summarized with a short conclusion.



AHB SYSTEM

System Outline

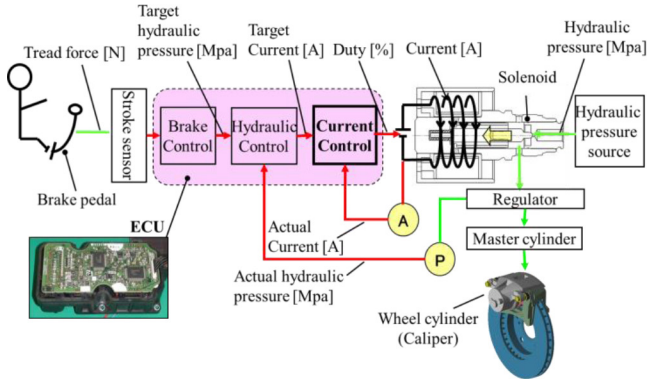


Figure 1. Constitution and operation of AHB system

The AHB system is a mechanically and electrically integrated system that controls hydraulic brake pressures through a digital control system composed of a microcomputer and the custom IC in an electronic control unit (ECU). The control system has a brake control unit, a hydraulic control unit, and a solenoid current control unit (Figure 1). The driver's brake pedal stroke is detected by a stroke sensor, and is transmitted to the microcomputer. The brake control unit calculates a target hydraulic pressure from the brake stroke and outputs it to the hydraulic control unit, which outputs a target current to the solenoid current control unit so that the real hydraulic pressure will match the target value. The solenoid current is controlled with PWM switching. The current control unit calculates a duty so that the real current will closely match the target value, and then modulates a MOSFET (double-diffused MOSFET or DMOS) switch on the custom IC. Through these control operations, the solenoid valve is actuated and the hydraulic pressure is applied to a wheel cylinder, which makes the brake work.

Requirement for Solenoid Current Sensing

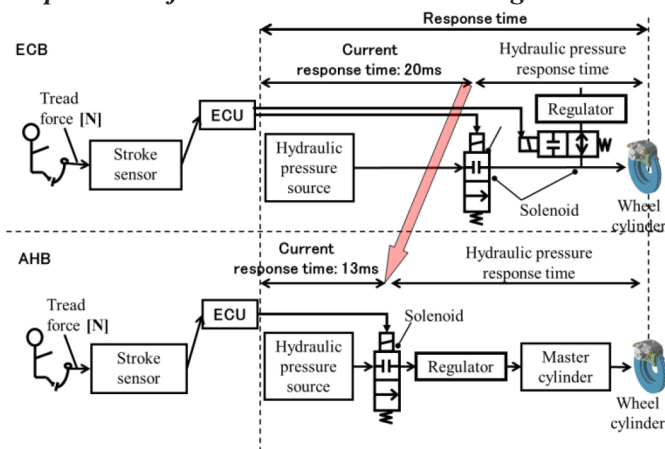


Figure 2. Comparison of ECB and AHB system.

Figure 2 shows a comparison of the conventional ECB system and the AHB system. The ECB system has two brake fluid paths to actuate the wheel cylinders, and the ECU changes the path in order to control the fluid pressure that is applied to the wheel cylinders. The AHB system has a single brake fluid path to actuate the wheel cylinders, so the ECU does not have to change the path, which

realizes a seamless brake feeling. And in the AHB system, the fluid pressure is transmitted to a wheel cylinder after going through the regulator. This reduces the sound generated from the linear solenoid valve by decreasing the fluid flow rate controlled by the solenoid. Because of the above system change, the requirement for the solenoid current control becomes stricter, which makes the current sensing one of the key technologies in the AHB system.

CUSTOM IC

IC Functions

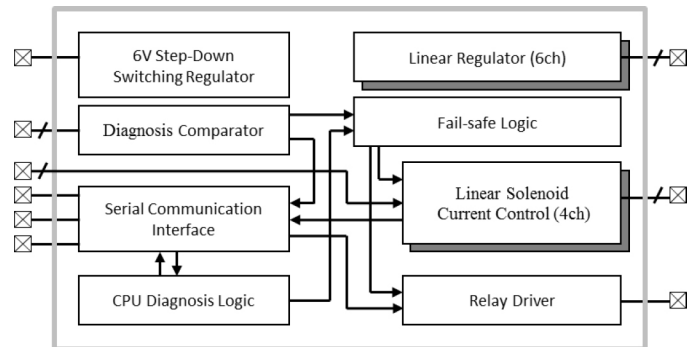


Figure 3. Block diagram of the custom IC.

The custom IC contains functions of 7 regulated power supplies, including 6 linear regulators and a 6V step-down switching regulator, 4 solenoid current control circuits, CPU diagnosis logic, serial communication interface with a microcomputer, relay drivers, and on-chip diagnosis logic. When the diagnosis circuits detect a malfunction, the system goes into the fail-safe mode.

Solenoid Current Control

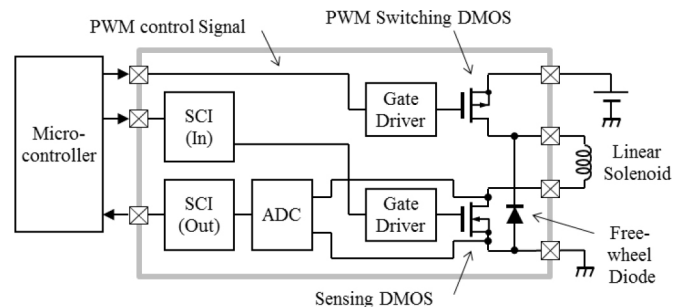


Figure 4. Block diagram of the solenoid current control circuit including the serial communication interface (SCI).

The block diagram of the solenoid current control is shown in figure 4. The solenoid current is controlled with PWM by the combination of the custom IC and the microcomputer, with the current control circuits of 4 systems working independently. The IC converts the solenoid current value to digital data with the on-chip current-to-digital converter, and transmits it to the microcomputer with serial multiplex communication. The microcomputer outputs the PWM control signal and modulates the PWM switching DMOS so that the current will match the target value. Here, the sensing DMOS is a MOS switch which shuts down the solenoid current when a system malfunction is detected in addition to a current-to-voltage conversion element which senses the solenoid current with the on-chip current-to-voltage converter.

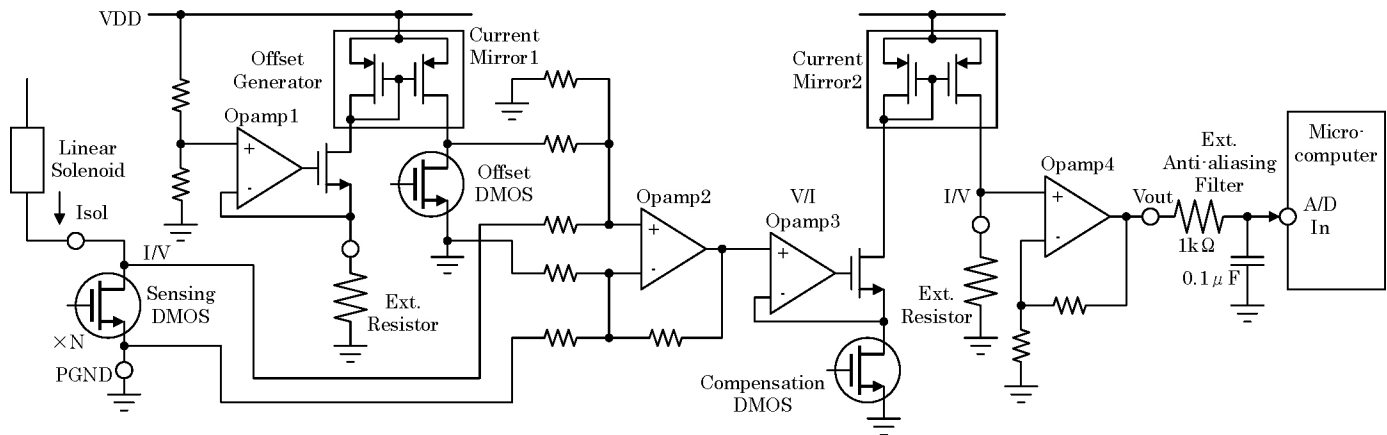


Figure 5. Former Current Sensing Circuit

CURRENT-TO-DIGITAL CONVERTER

As described before, high-performance solenoid current sensing is one of the key technologies in the AHB system. Because the PWM control is used, the ripple current synchronizing with the PWM switching frequency of 15.625kHz is superimposed onto the solenoid current. It is required that a solenoid current sensing circuit detect only the signal component while excluding the ripple components, and the current value be converted to digital data in order to be directly read by the microcomputer, a digital controller, and be transmitted with serial communication to reduce the number of IC terminals. On the other hand, the AHB system needs eight current sensing circuits since it has four independent current control systems with redundant sensing circuits for mutual monitoring. Therefore, reduction of chip area usage for each sensing circuit is also required to integrate the eight sensing circuits on a single chip.

Target Performances

- Resolution : 12 bits, or better than 11 bits in ENOB*
*ENOB : Effective number of bits
- Signal group delay : max 200μs (Excluding serial communication)
- Filtering : Removal of the ripple components with PWM switching
- Low cost : Small chip area, minimal external elements and pins

Prior Art

Figure 5 is the schematic diagram of the solenoid current sensing circuit used in the ECB system of the former model. The schematic is symbolized to a certain extent and circuit elements unnecessary for explanations of circuit functions, such as protective circuits, are omitted for simplicity. In this conventional current sensing circuit, it is a “current-to-voltage converter” which is placed on the custom IC. The circuit converts a solenoid current, I_{sol} ($=0 \sim A$), which is to be measured, to a corresponding voltage linearly. This output voltage is applied to an A/D converter input of the microcomputer and converted to a digital data.

The circuit function is described as follows. The sensing DMOS, which also serves as a low-side switch, is in an on state at the time of a current measurement, and the solenoid current, I_{sol} , is converted to

the voltage with the on-resistance, R_{on} (I/V conversion). Here, a constant offset voltage is added to the output voltage so that the opamp output will not be saturated to the GND side to maintain a linear characteristic from zero solenoid current. A constant current is generated by Opamp1 and an external resistor (metal-film for good temperature variation characteristics), and is output as the drain current of a DMOS (Offset DMOS) with the same device structure as the sensing DMOS, which generates a voltage corresponding to the offset current, I_{ofs} (0.32A). The voltage is added with Opamp2, and the output voltage is shifted to the positive side.

Because the DMOS on-resistance has process, voltage, and temperature (PVT) variations, the opamp2 output voltage varies in proportion to the on-resistance. This circuit compensates the variation due to the on-resistance through the next two steps of analog circuit operation (Compensation V/I and I/V conversions). In the first step, Opamp3 with a MOSFET source-follower applies the same voltage as the output of opamp2 to the drain of a DMOS (Compensation DMOS). Because DMOS on-resistances with the same device structure on a single IC chip are well matched, the variation due to the on-resistance is canceled, and a current proportional to $(I_{sol} + I_{ofs})$ flows to the drain of the compensation DMOS (V/I Conversion). In the second step, this drain current is mirrored by a current mirror (Current mirror 2), and by outputting the current to another external resistor, a voltage proportional to $(I_{sol} + I_{ofs})$ is generated between the terminals of the resistor (I/V Conversion). A non-inverting amplifier with Opamp4 amplifies the voltage and gives the final output. Through this analog compensation process, the current-to-voltage conversion output compensated for the DMOS on-resistance is provided.

This voltage output is applied to an A/D converter input of the microcomputer through an RC filter (anti-aliasing filter) and digitized. However, the analog 1st-order RC filter does not completely reject the current ripple due to PWM switching, so the final solenoid current signal is obtained after averaging several samples using logic embedded in the microcomputer.

In this conventional circuit each sensing channel uses a number of analog circuits including opamps, and because the compensation V/I and I/V conversions are necessary to cancel on-resistance variations of the DMOS, its circuit area is relatively large. In