Developments in Precision Power Train Sensors

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OVERVIEW: The fuel economy and emissions performance demands on vehicle power trains are becoming more stringent for reasons relating to global environmental protection and the rising price of oil. There has also been a change in thinking on the measurement of emissions and fuel economy toward allowing for conditions where the temperature and humidity are closer to real driving conditions. Other changes include the electrification of power trains, such as in hybrid vehicles, and improvements in the running efficiency of internal combustion engines that result in more frequent use of engine operating modes in which sensor operation is more difficult, such as the Atkinson cycle. Hitachi Automotive Systems, Ltd. is supporting ongoing progress in power train control by making further improvements in sensor accuracy.

INTRODUCTION

HITACHI supplies customers around the world with a variety of systems for the driving, cornering, and braking of vehicles. By using a range of different sensors to determine conditions in the power train, vehicle body movements, and what is happening around the vehicle, these systems ensure a driving experience that is safe and comfortable, and that is conscious of the global environment (see Fig. 1).

Automotive power trains have made rapid progress on electrification and reducing fuel consumption in recent years. This article describes advances in the performance of the sensors used in these power trains, looking at micro electromechanical system (MEMS) air flow sensors that reduce the error in intake pulsation, the integration of air intake relative humidity sensors and pressure sensors, and the adoption of digital signal output for sensors with network connectivity.

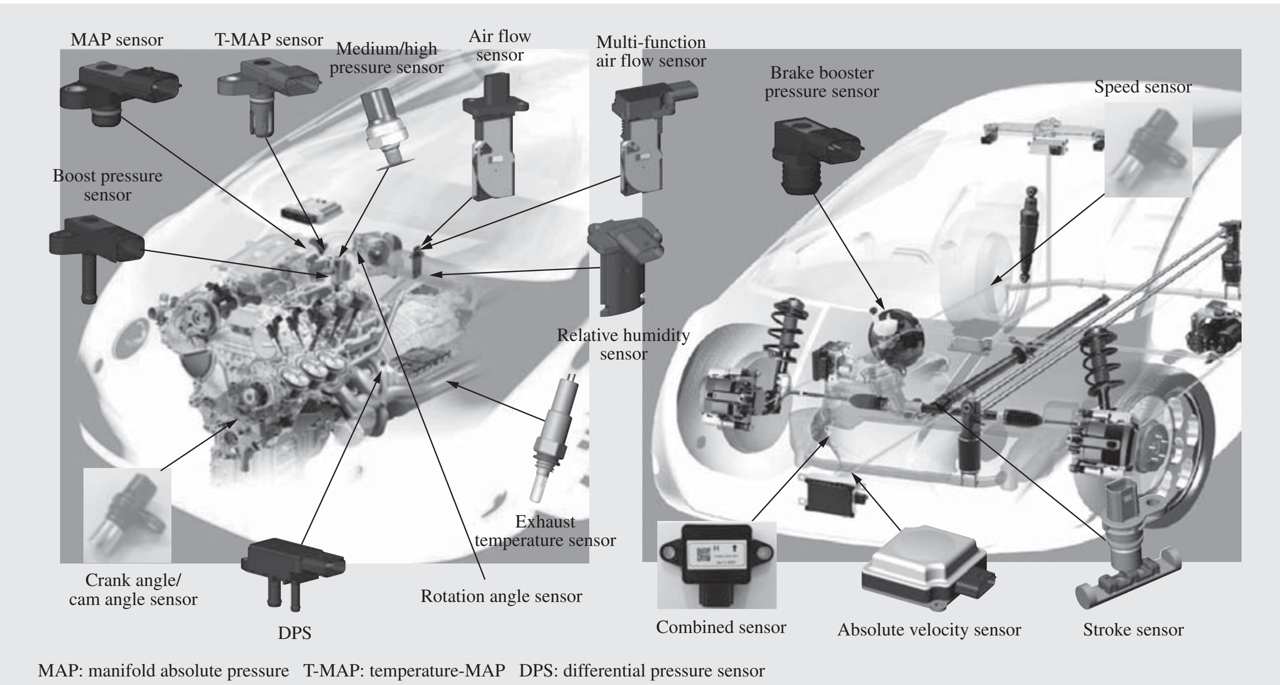

Fig. 1—Hitachi Power Train Sensors.
Modern vehicle power trains incorporate a variety of sensors that are used by control systems to deliver maximum environmental performance. Improvements in sensor accuracy lead directly to better control system performance.

MEMS AIR FLOW SENSORS

Since commercializing its first hot-wire air flow sensor in 1981, Hitachi has supplied a total of 200 million air flow sensors of various types over numerous generations. These have included the MEMS air flow sensors[1] introduced in 2005 that use a silicon diaphragm detection element to measure air flow in both directions. The second generation of these sensors currently in production operate the detector at a higher temperature for better anti-fouling and use 5-V drive to reduce power consumption. The third generation of sensors are currently being set for production. They are designed for lower cost and to achieve high precision when operating at a high level of intake pulsation.

Sensors for Engines with High Level of Intake Pulsation

The functions and performance sought in MEMS air flow sensors depend to a large extent on advances in the engines in which they are used.

When engines used the Otto cycle, the intake air flow remained unidirectional (into the engine) over most operating conditions. Modern engines, however, have features that include reduced pumping losses through the use of a high exhaust gas recirculation (EGR) ratio, and use of the Miller cycle (a variation on the Atkinson cycle) to provide a high expansion ratio. A consequence of this is that reverse flow (air flow out from the engine) is very common.

In Miller type Atkinson cycle engines, for example, which use valve timing control (VTC) to significantly delay the intake valve close (IVC) timing angle, most of the in-drawn air is expelled again by the piston, resulting in reverse flow and stronger pulsation. Also, when an engine's EGR ratio is raised, assuming the same total volume of air-fuel mixture is supplied to the cylinder, the amount of air is reduced by the amount of exhaust gas used. For the sensors that measure the air flow rate, this means that even if the size of the pulsations remains the same, they become larger in relative terms because of the reduction in mean air flow (see Fig. 2).

Hitachi divides the pulsation amplitude by the mean forward air flow to quantify it as the pulsation amplitude ratio. If the pulsation amplitude ratio exceeds 200%, this indicates that there is a period in which the air flow is fully reversed. As improvements are made in engine performance, this pulsation amplitude ratio is rising with each new vehicle generation (see Fig. 3).

As advances in engines and engine control result in a strongly pulsing flow in the vicinity of the air flow sensors, techniques for reducing error are important even in the case of MEMS air flow sensors that can cope with bidirectional flow.

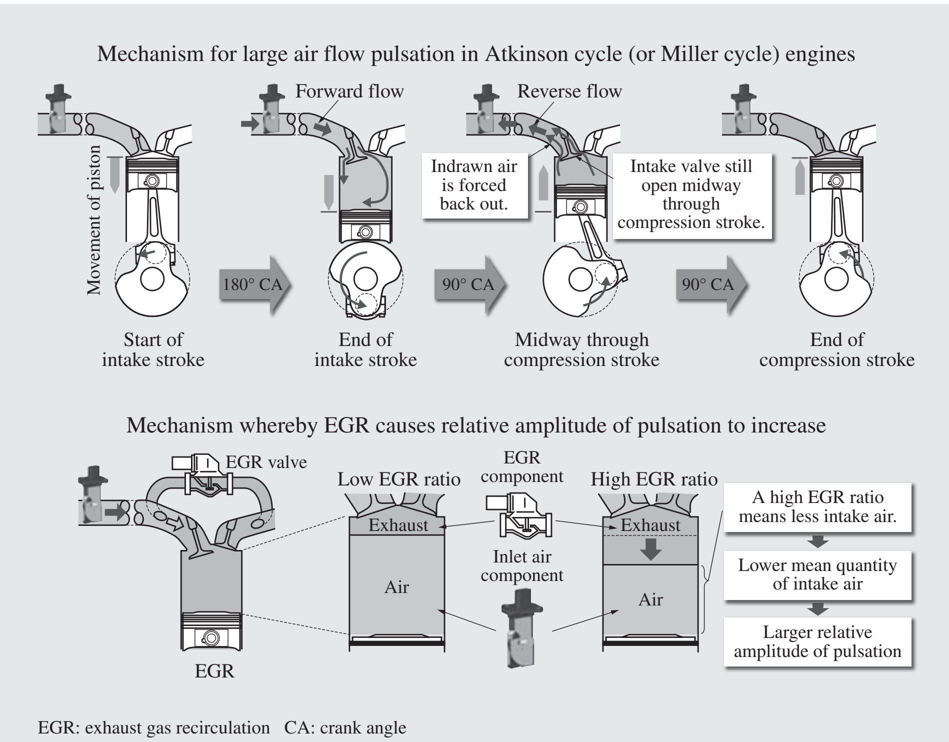

Fig. 2—Flow Pulsation Mechanism.
As Miller type Atkinson cycle engines delay the intake valve close timing until the middle of the compression stroke, a large amount of air is forced back out the inlet, resulting in large pulsations. If a large EGR is used, the increased use of recirculated exhaust gas reduces the amount of air taken in, making the pulsations larger relative to the intake air.

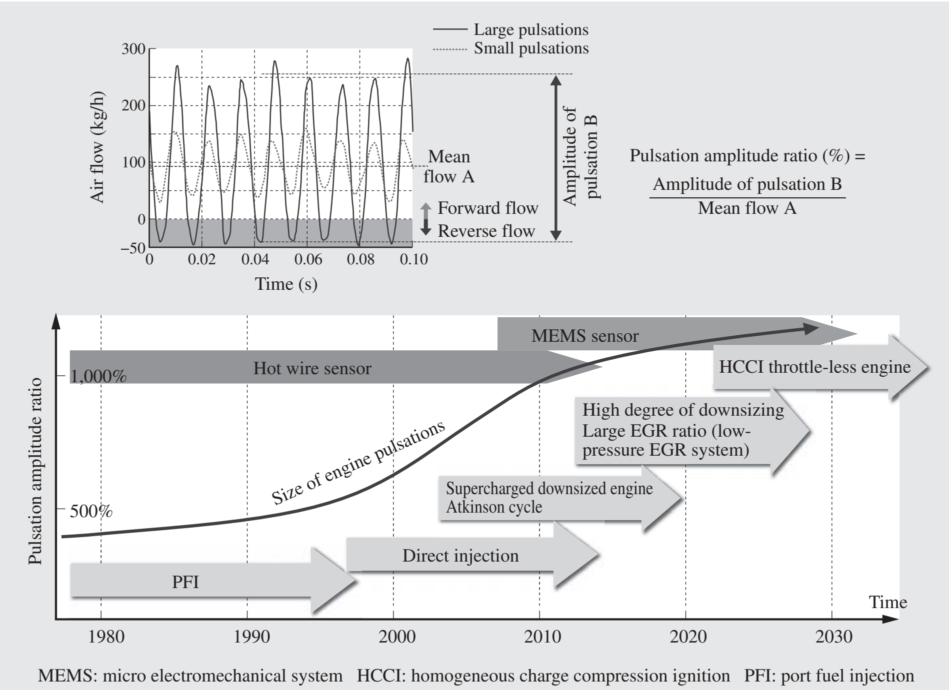

Fig. 3—Flow Pulsation Mechanism.
For quantitative measurements, Hitachi defines the size of pulsations in terms of their amplitude as a proportion of mean air flow. This pulsation amplitude ratio is increasing as engines become more advanced, and the accuracy of air flow measurement under pulsation conditions is closely related to advances in engine control.

Techniques for Reducing Air Flow Measurement Error Due to Pulsation

The error that occurs when inlet pulsations are large is due to a number of causes. The output signal of the air flow sensor is required to always represent the mean forward air flow. Accordingly, however accurate the sensor may be at measuring the forward air flow, the overall sensor error will be large if there is a measurement error in the reverse flow component or if this is not compensated for appropriately. Pulsation error has a variety of causes which are always interrelated, the main ones being the flow detector having a response that is too slow, non-linearity error (due to non-linear characteristics), and turbulence error (when turbulence in the air flow sensor itself causes suction when the flow reverses).

While this has been dealt with in the past using correction measures such as conventional signal filter processing or by the shape of the bypass channel in the air flow sensor, these provide inadequate correction for air flows with a very high level of pulsation.

To solve this problem, Hitachi Automotive Systems, Ltd. and Hitachi Research Laboratory jointly developed an application-specific integrated circuit (ASIC) digital signal processor (DSP) specifically for use in air flow sensors. The air flow sensor significantly reduces pulsation error by utilizing the high-speed computing capabilities of the DSP to process the signal internally. This includes performing separate signal correction for the forward and reverse directions, linearity processing in which the flow rate signal is converted to its physical amount before applying correction, and precise temperature compensation for the pulsation characteristics.

By optimizing the length of the secondary channel (the bypass through the sensor) and the inlet for reverse flow (outlet) to stabilize the air flow in the detector, Hitachi has succeeded in providing sufficient accuracy for trouble-free engine operation even under high levels of pulsation, such as pulsation amplitude ratios approaching 1,000% at which the sensor signal was unable to be used in the past (see Fig. 4).

MULTI-FUNCTION AIR FLOW SENSORS

While the predominant configuration has long been to connect different single-function sensors to the engine control unit (ECU), there is also growing demand for combining multiple sensors in a single multi-function package and performing mutual correction to improve their overall accuracy. In 2011, Hitachi became the first supplier to commence production of a multi-function air flow sensor that also included a relative humidity sensor and pressure sensor (see Fig. 5).

Hitachi is also working on the development of a new generation of devices that use a digital interface to improve the accuracy of the sensor signal passed to the ECU, incorporate network connectivity to reduce wire harness requirements, and provide more flexible onboard diagnostics (OBD).

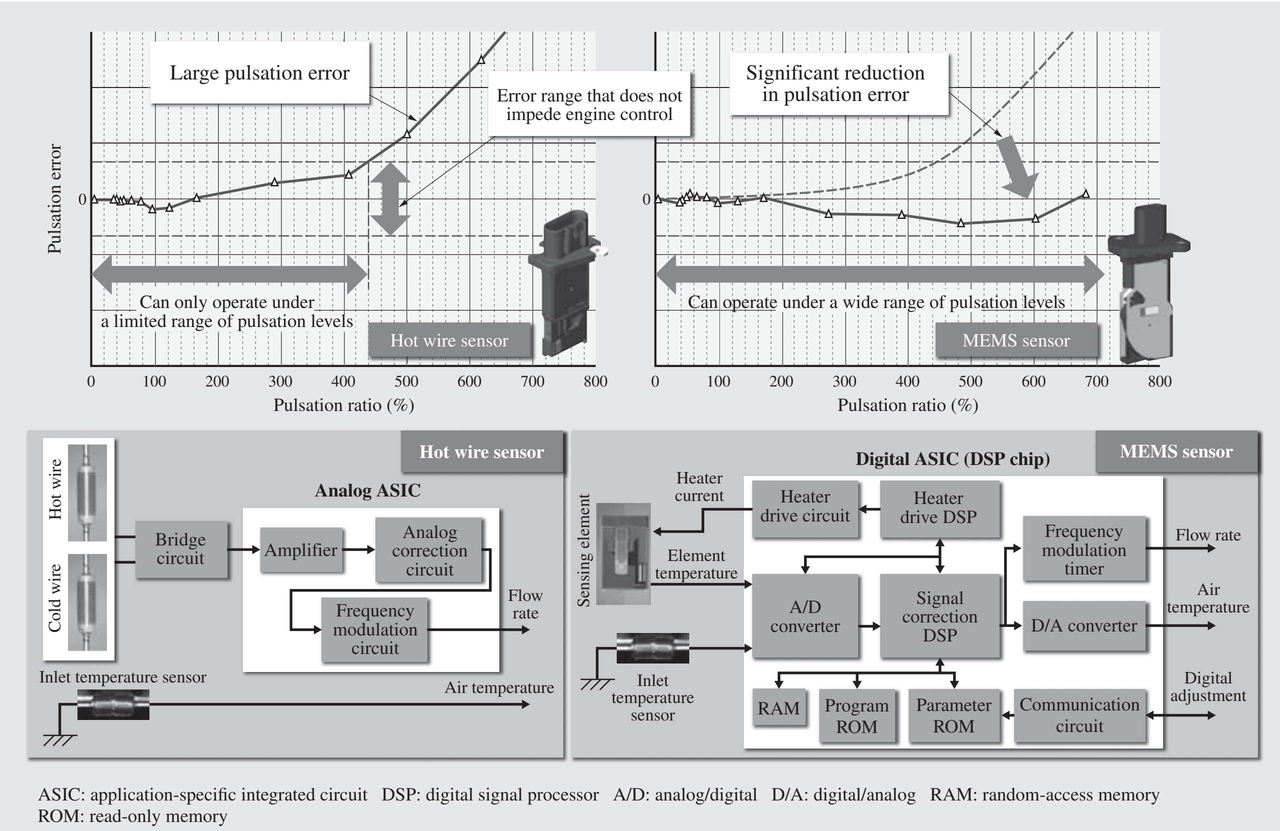

Fig. 4—Reducing Error in Air Flow Measurement Due to Pulsation.
As there is a limit to how accurately a pulsing flow can be measured using analog circuits, MEMS air flow sensors include a special-purpose DSP for internal digital signal processing to ensure sufficient accuracy to prevent any loss of engine control performance even when there is a very high level of flow pulsation.

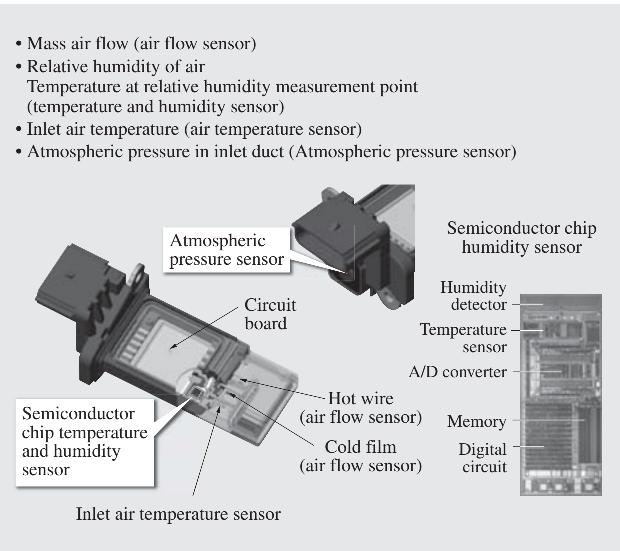

Fig. 5—Multi-function Air Flow Sensor.
In addition to its air flow sensor function, this sensor also measures the relative humidity and the pressure in the inlet duct. This allows the engine control to adapt to changes in weather, driving, and other conditions, and means that the engine control margins previously included to allow for changes in humidity can be allocated instead to fuel economy or other improvements.

Use of Multiple Sensors to Improve Control Accuracy

In addition to the mass air flow traditionally measured by sensors, the physical properties of the air taken in by the engine also include such things as moisture content (water vapor) and the pressure at the measurement point. Changes in these properties will cause an error in the mass air flow measured by the sensor that can be as high as several percent at low flow rates. This is because both hot wire and MEMS sensors work on the principle of detecting the transfer of heat by the air, and therefore are influenced by moisture-induced changes in the physical properties of the air.

Also, engine factors such as ignition performance, EGR limit, and fuel temperature are affected by the amount of moisture in the intake air, and these result in large changes in outcomes such as fuel consumption and the amount of pollutants produced. Accordingly, a key factor in improving environmental performance is to control the engine, along with exhaust gas treatment and other systems, in accordance with changes in the moisture content of the intake air.

While the existence of these errors was known in the past, the regulatory levels were not sufficiently tight for them to be a problem. With the market's emphasis on low fuel consumption and steadily more stringent regulations, however, semiconductor-chip-based relative humidity sensors have been added to multi-function air flow sensors to correct for the error caused by the moisture in intake air.

Relative humidity sensors are capacitive sensors. They consist of a capacitor with a dielectric made of moisture-sensitive polymer with a permittivity that varies as it absorbs water molecules from the air, the extent of which can be detected from the variation in the sensor's capacitance. These relative humidity sensors also incorporate a highly accurate temperature sensor. The absolute humidity of the air can then be calculated from this temperature and the relative humidity.

As the relative humidity varies with pressure, it is possible to obtain a very accurate measurement of the moisture being taken into the engine by using information from the built-in pressure sensor to correct for this effect.

The sensor also includes a microprocessor to provide the flexibility to work with various different engine control systems, allowing output of both the raw uncorrected sensor signals and the corrected values (see Fig. 6).

Accuracy Improvements in Sensor Signal Transmission

Improving sensor accuracy is pointless if the accuracy is degraded during signal transmission. Traditionally, most sensor signals have either been analog voltage outputs or frequency-modulated outputs that worked by varying a pulse frequency. However, this results in degradation of the final accuracy of the sensor signal due to errors that occur during signal transmission, such as fluctuations in the ground potential or the temperature characteristics of the modulation reference frequency, or due to conversion error in the analog-to-digital converter (ADC) in the ECU that converts the analog signal to a digital value.

As a result, high-precision sensors are increasingly converting signals to digital form to avoid these errors. Single-edge nibble transmission (SENT) communications is one example of a method for converting sensor signals to digital form. It can send two sensor signal channels over a single wire and can include use of cyclic redundancy check (CRC) error detection[(2)].

As it is also possible to multiplex multiple signal channels, the technique is suitable for applications like the multi-function air flow sensor that require the output of a number of sensor signals.

The SENT protocol provides one-way (sensor to ECU) communications and works by converting a

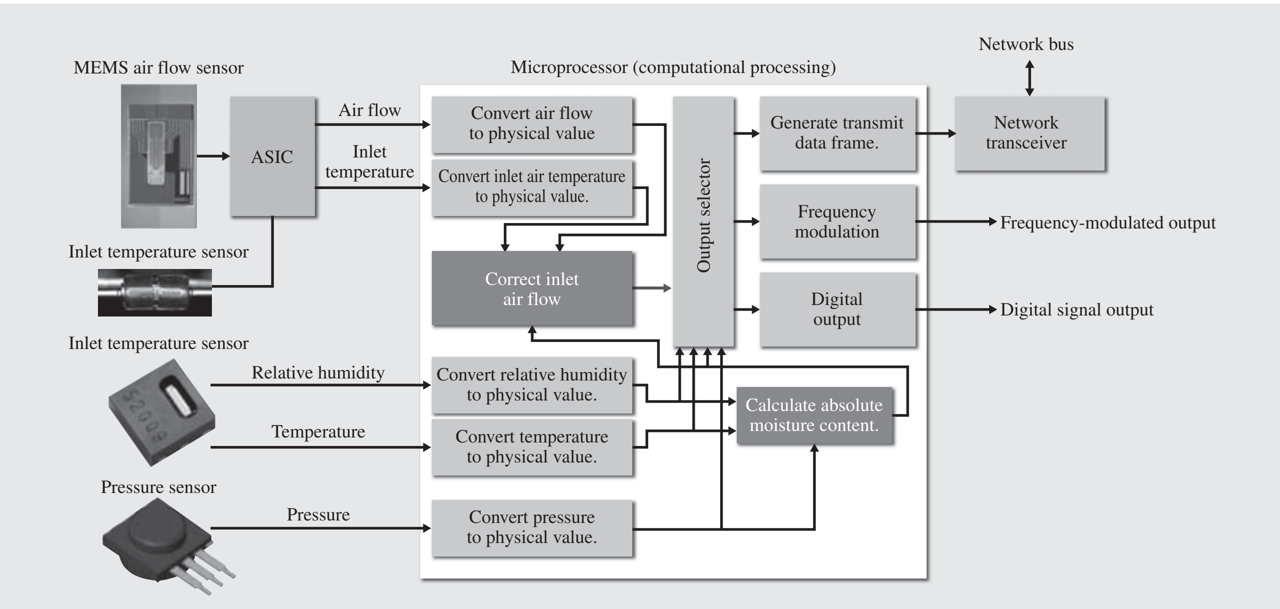

Fig. 6—Use of Multiple Sensors to Improve Accuracy (Multi-function Air Flow Sensor).
Use of multi-function sensors can improve overall signal accuracy because it means that information from certain sensors can be used to correct other sensor signals. This example shows how the relative humidity measurement can be corrected using pressure to calculate the absolute humidity. This can then be used to correct the inlet flow rate.

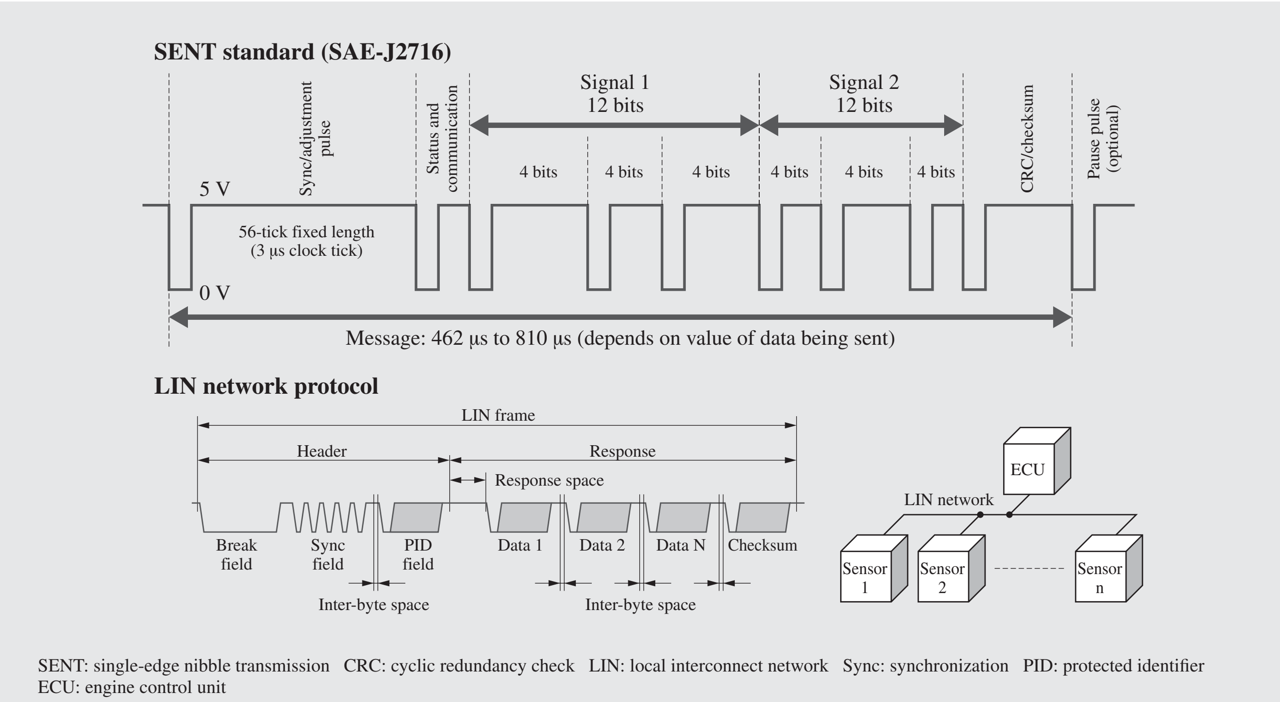

Fig. 7—Digitization of Sensor Output Signal.
The ability of SENT to transmit two signals per message with a cycle time of less than 1 ms makes it a suitable protocol for digital sensor signals. Already used for angle sensors, it is anticipated that its simplicity will see it used more widely in future. LIN, meanwhile, is a low-speed network that is already widely used in vehicle electronics, and it is starting to be used in power trains because of its flexibility and its ability to provide bidirectional communications over a single wire.

conventional analog signal to digital form. In addition to SENT, the sensors currently under development will also support the local interconnect network (LIN) protocol[3] (see Fig. 7). Hitachi is working on sensors that combine higher accuracy with flexibility, such as by taking advantage of the ability to communicate in both directions to improve accuracy by only activating those sensors that are required at particular time, as specified by a request from the ECU. Because converting sensor signals to digital form and providing network capabilities improves flexibility while reducing the loss of accuracy in the signal transmission process, this is the best type of interface for precision sensors.

CONCLUSIONS

This article has described advances in the accuracy of automotive sensors, including improvements in the measurement accuracy of MEMS air flow sensors under conditions of high pulsation, the integration of multi-function sensors, and the use of digital signals for sensor output.

The benefits of using precise, high-performance sensors to determine conditions such as those in the power train, vehicle body movements, or what is happening around the vehicle include improving the safety of vehicles and their power trains, resource saving, and global environmental improvement.

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