

# Development of Cylinder Pressure Measurement System Using Adaptive Calculation

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## ABSTRACT

This paper discusses the development of a system enabling real-time measurements of combustion pressure in an internal combustion engine, using a comparatively low-cost polycrystalline piezoelectric element. Tests conducted using a mass production vehicle showed that by using the measured cylinder pressure, the status of combustion could be measured across the entire range of driving conditions, enabling misfires to be precisely detected. To date, despite their comparatively low cost, the use of piezoelectric elements in mass production vehicles has represented a challenge, because the temperature characteristics of the elements in the use environment, age degradation, and other factors may cause variations in output. This research therefore studied the variation in sensor output in terms of each causal factor. In addition, adaptive calculations were performed to enable the identification of corrective parameters to be used, to match the measured cylinder pressure to estimated reference pressures for vehicle operation, thus enabling stable cylinder pressures to be measured, even if temperature characteristics change or the output deteriorates.

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## 1. Introduction

Today's increasing focus on environmental issues is generating demands for enhanced exhaust gas cleaning performance and increased combustion efficiency in automotive gasoline engines. In general, the air-fuel ratio of conventional gasoline engines is precisely controlled to maximize the performance of the catalytic converter. Additional enhancement of combustion efficiency and the ability to maintain an optimum state of combustion are now necessary to enable controllability to be increased. This would necessitate the use of a cylinder pressure sensor that measures the state of combustion in each cylinder in real time. However, reaching the stage of mass production of such a sensor represents a considerable technological challenge. Years of research have been expended on development, but few sensors have reached the stage of mass production<sup>(1)-(4)</sup>. Research has been conducted on the application of a simple using a piezoelectric element in a diesel engine<sup>(5), (6)</sup> in recent years.

Piezoelectric elements can be divided into single

crystal and polycrystalline types. Single crystal piezoelectric elements possess a reliable temperature characteristic, ensuring stable output across the range of engine operating temperatures, from low to high. However, they are comparatively expensive, and are therefore not suitable for use as sensors in mass production engines. By contrast, polycrystalline piezoelectric elements are comparatively inexpensive, but display major changes in sensitivity in response to changes in temperature. For this reason, it would be challenging to achieve a stable output using these elements as cylinder pressure sensors in automotive engines, a use environment in which the temperature range exceeds 210 °C (-40 to 170 °C).

The research discussed in this paper therefore developed a system enabling real time monitoring of the status of combustion, based on a correction method using adaptive calculation in which software is employed to correct changes in the sensitivity of a polycrystalline piezoelectric element. This research has enabled stable measurement of the cylinder pressure of a mass production engine using a polycrystalline piezoelectric element.

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Table 1 Engine specifications

|                                 |                       |
|---------------------------------|-----------------------|
| Engine type                     | V6                    |
| Displacement (cm <sup>3</sup> ) | 2997                  |
| Bore × stroke (mm)              | 86 × 86               |
| Compression ratio               | 10.0                  |
| Valve train                     | 24-valve<br>SOHC VTEC |
| Fuel                            | Regular unleaded      |

## 2. System Configuration

### 2.1. Test Engine

The US ACCORD 3.0 L V6 engine was used in the development of the system. Table 1 shows the specifications of the engine.

### 2.2. Cylinder Pressure Sensors

As shown in Fig. 1, the cylinder pressure sensors are fixed in place between the cylinder heads and the plugs. The use of this layout means that no major modification of the valve layout of mass production engines is required, giving the sensors a higher degree of general applicability.

Figure 2 shows the sensor structure. The sensor is

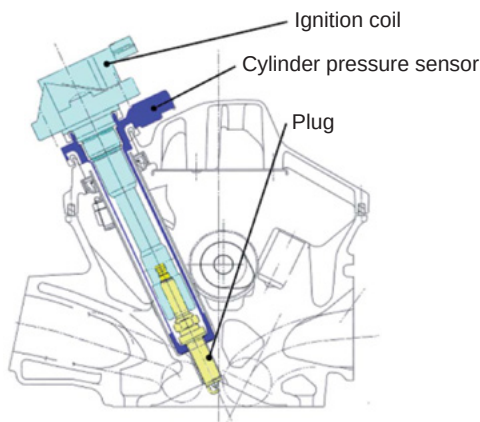


Fig. 1 Installation of cylinder pressure sensor

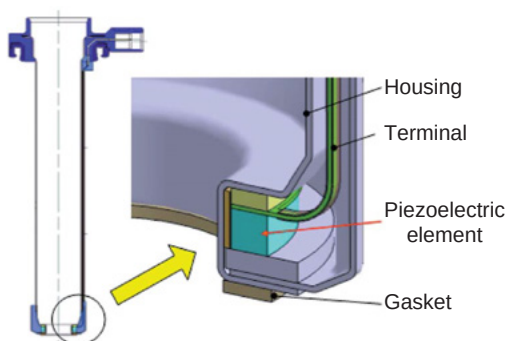


Fig. 2 Cylinder pressure sensor structure

basically a piezoelectric element contained in a cylindrical housing, forming a simple washer structure that senses strain between the heads and the plugs. An electrode at one end of the element is connected to the exterior by means of a terminal that sits alongside the sensor housing. This layout enables the sensor on the engine assembly line to fit without affecting the ability to mount the plugs.

Figure 3 shows the principle of detection of cylinder pressure. When combustion pressure is generated, the pressure generates strain in the direction the plugs are pushed. This strain is transmitted by the plugs and reaches the sensors. This strain changes the pressure on the piezoelectric element in the sensor, producing a minute  $\Delta L$  deformation of the element. This deformation produces drift in the electrical charge at each end of the element. When a change in the electrical charge is detected, it is converted into a voltage using a charge amplifier, enabling detection of the cylinder pressure (Fig. 4).

### 2.3. System Configuration

In order to realize high-speed calculation processing of the signal from the cylinder pressure sensor in real time, a cylinder pressure unit was newly developed to enable data transfer to the Engine Control Unit (ECU) by means of a Controller Area Network (CAN). The system

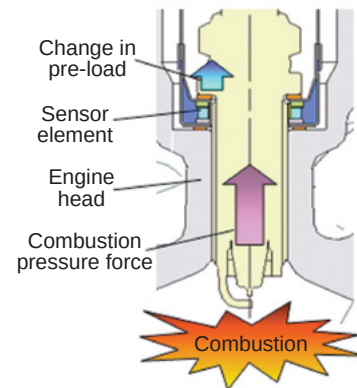


Fig. 3 Pressure sensing mechanism

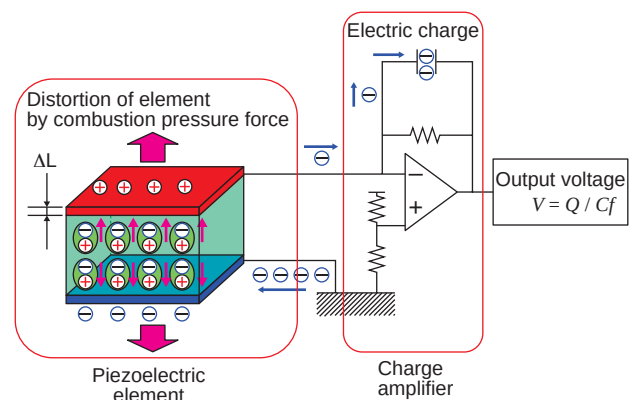


Fig. 4 Function of charge amplifier

configuration is shown in Fig. 5.

Within the cylinder pressure unit, the change in the electrical charge of the sensor element is converted to a voltage by a charge amplifier. An AD converter is then used to convert this voltage into a digital signal, after which it is input to a Central Processing Unit (CPU). The CPU calculates the crank angle based on the crank pulse and the cylinder pulse, and calculates the cylinder pressure for each crank angle. A 100 MHz CPU was used in the prototype unit, and the AD converter employed a 50 kHz sampling rate. This enables cylinder pressure for every 1 deg. of crank angle to be measured up to the red zone of 6800 rpm and above.

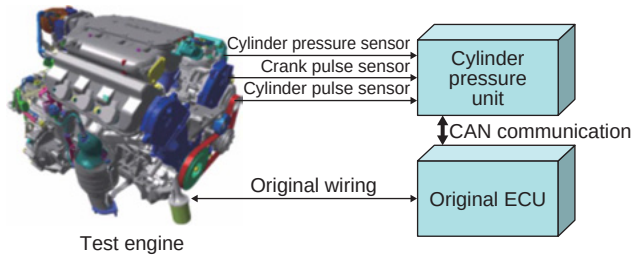


Fig. 5 System configuration for cylinder pressure sensing

### 3. Correction of Sensor Output using Adaptive Calculation

#### 3.1. Variation in Sensor Sensitivity

The basic properties of lead titanate ( $\text{PbTiO}_3$ ) are that it possesses a perovskite-type crystal structure, like standard polycrystalline piezoelectric materials, and produces piezoelectricity (ferroelectricity) by means of asymmetrical displacement of crystals. In addition, the piezoelectric constant and relative dielectric constant of the material display a comparatively high rate of increase with increases in temperature, and a noticeable increase at around the Curie temperature. In other words, it displays a high rate of change in sensitivity and a high level of pyroelectricity in relation to changes in temperature. To enable this material to be used as a cylinder pressure sensor in an automotive engine, it was necessary to study other factors causing variation in sensitivity and degradation of characteristics, in addition to the range of variation and degradation. The various factors were therefore isolated, and the variation in the sensitivity of the sensor in an actual use environment was studied, including consideration of durability.

##### (1) Initial variations

Variations that occur after production caused by variations in the solid parts of the element, the shape of the case, and the load applied during assembling.

Table 2 Sensor variation

|                                   |                             |              |
|-----------------------------------|-----------------------------|--------------|
| Initial variation                 | 2500 pC/MPa                 | $\pm 27\%$ * |
| Axial tension characteristics     | Maximum axial tension       | $+2\%$ *     |
|                                   | Minimum axial tension       | $-25\%$ *    |
| Temperature characteristics       | $170\text{ }^\circ\text{C}$ | $+160\%$ *   |
|                                   | $-40\text{ }^\circ\text{C}$ | $-35\%$ *    |
| Engine revolution characteristics | 3000 rpm or more            | $-44\%$ *    |
| Durability degradation            | 550000 mile                 | $-30\%$ *    |

\*  $3\sigma$  variation

##### (2) Axial tension characteristics

Changes due to variations in torque when the plugs are mounted and the settling of the screws.

##### (3) Temperature characteristics

The piezoelectric constant changes with changes in temperature. This temperature-dependence of polycrystalline piezoelectric elements represents an impediment to their use as mass produced sensors.

##### (4) Engine speed characteristic of screws

Combustion pressure that enters through gaps in the screws in the plugs and heads differs at low and high engine speeds, resulting in changes in the sensitivity characteristic. This characteristic should be considered due to the adoption of a configuration in which the sensor is fixed in place between the plugs and the heads.

##### (5) Decline in durability

Degradation of piezoelectric elements can be divided into electrical degradation (decline in piezoelectricity) and mechanical degradation (damage to the element). With regard to mechanical degradation, this project used the guaranteed pressure resistance; it determined electrical degradation from use conditions and usable life.

Table 2 shows the range of each of these variations in a 3.0 L V6 engine. The respective variations were calculated using  $3\sigma$ .

Multiplying the variables in the case of an increase in sensor output

$$\begin{aligned} V_{out} &= a \times b \times c \times d \\ &= 2500 \times 1.27 \times 1.02 \times 2.6 \\ &= 8420 \end{aligned} \quad (1)$$

$a$ : Initial median value

$b$ : Initial maximum coefficient

$c$ : Maximum axial tension coefficient

$d$ : Upper limit of temperature sensitivity coefficient

Multiplying the variables in the case of a decrease in sensor output

$$\begin{aligned} V_{out} &= a \times e \times f \times g \times h \times i \\ &= 2500 \times 0.73 \times 0.75 \times 0.65 \times 0.56 \times 0.7 \\ &= 368 \end{aligned} \quad (2)$$

- $a$ : Initial median value
- $e$ : Initial minimum coefficient
- $f$ : Minimum axial tension coefficient
- $g$ : Lower limit of temperature sensitivity coefficient
- $h$ : Engine speed characteristic coefficient
- $i$ : Decline in durability coefficient

As the results of Eqs. (1) and (2) above show, the sensitivity of the sensor varied from 368 pC/MPa to 8420 pC/MPa, necessitating correction of a more than 20-fold variation.

In addition to the piezoelectric constant (sensitivity), the relative dielectric constant of the sensor also varies with changes in the temperature of the sensor. This means that a pyroelectric effect producing variance in the output voltage of the charge amplifier according to temperature changes.

As Fig. 6 shows, in order to correct this characteristic, the sensor output is reset at top dead center before intake, and the voltage before and after the reset is monitored and its gradient is corrected.

### 3.2. Correction of Sensor Output Using Adaptive Calculation

Having elucidated the variation in sensitivity characteristics of a polycrystalline piezoelectric element above, this section discusses a real-time measurement method in which adaptive calculation is employed to correct sensitivity.

A single crystal piezoelectric element of the type generally employed as cylinder pressure sensors, manufactured by Kistler (Type 6052B) was employed as the benchmark sensor, and the new method was developed to achieve an output equivalent to that of this benchmark sensor.

Figure 7 shows an outline of the sensor output correction method.

- (1) Calculations are conducted to determine the cylinder pressure from engine operating conditions ( $P_{model}$ ).

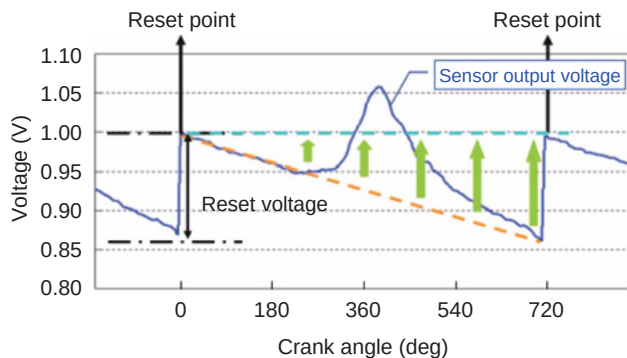


Fig. 6 Reset timing of sensor signal and signal correction

- (2) The cylinder pressure when the engine is motoring is measured using the benchmark sensor, and the calculated cylinder pressure is corrected using a correction coefficient in order to match the measurement from the benchmark sensor, producing a benchmark estimated cylinder pressure during motoring ( $P_{modelk}$ ).
- (3) Because the cylinder pressure during the compression stroke does not vary, even if there is a change in the status of combustion, the estimated motoring cylinder pressure determined in (2) can be used to enable real-time correction of the sensor signal via adaptive calculation, thus enabling the determination of cylinder pressure for each crank angle.

These points are explained in detail below.

- (1) An engine model is calculated from the engine operating state. From the configuration of the engine, the crank angle and piston position can be expressed by Eq. (3) as Fig. 8 shows.

$$x = r \left\{ (1 - \cos\theta) + \lambda - \sqrt{\lambda^2 - \sin^2\theta} \right\} \quad \because \lambda = l/r \quad (3)$$

The cylinder volume,  $V$ , can therefore be expressed by Eq. (4).

$$V = V_{dead} + A_{pstin} \cdot r \left\{ (1 - \cos\theta) + \lambda - \sqrt{\lambda^2 - \sin^2\theta} \right\} \quad (4)$$

$V_{dead}$ : Dead volume

$A_{pstin}$ : Piston TOP area

From the gas equation of state, the cylinder pressure,  $P$ , can be expressed by Eq. (5).

$$P = GRT / V \quad (5)$$

$G$ : Intake air amount

$T$ : Intake air temperature

$R$ : Gas constant

Because compression is adiabatic, the gas temperature varies with the volume  $V$ , and can be expressed by Eq. (6).

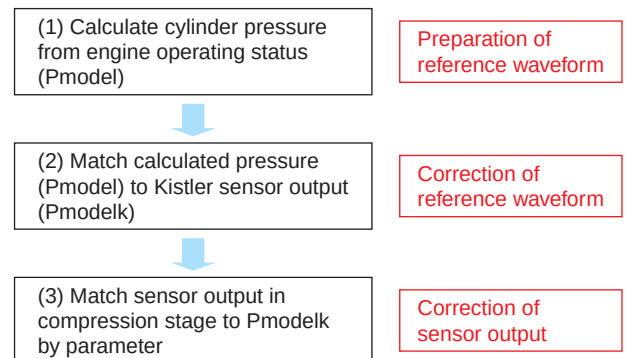


Fig. 7 Method of sensor signal correction

$$P_{model} = GR \frac{T_1}{(V_2/V_1)^{k-1}} / V \quad (6)$$

- (2) Because of inter-molecular force in the gas, the cylinder pressures in the physical model and the measured cylinder pressures do not match. The correction factors  $K_0$  and  $C_0$  are employed to make the cylinder pressure previously measured using the benchmark sensor and the model equation discussed above match. Following correction, the model equation becomes Eq. (7), and  $P_{modelk}$  matches the output of the benchmark sensor. A figure of 1.330 was used for the ratio of specific heat,  $k$ .

$$P_{modelk} = GR \frac{T_1}{(V_2/V_1)^{k-1}} / V \times K_0 + C_0 \quad (7)$$

As Fig. 9 shows, the correction coefficients  $K_0$  and  $C_0$  are set as a map of engine speed and amount of intake air.

- (3) In this section, the method of identifying the actually measured sensor output in the engine model equation will be explained. Exploiting the fact that the cylinder pressure during the compression stroke matches that of the engine model regardless of the state of combustion, a waveform during the compression stroke that corresponds with the waveform in the model is identified. Here, the least squares method is employed, with Eq. (8) being used to minimize error in terms of the difference between the designated

pressure during the compression stroke,  $P_{modelk}$ , and the actually measured cylinder pressure,  $P'$ . Partial differentiation of the error functions  $a$  and  $b$  to make  $P_{modelk} - P' = 0$  gives  $a = K_1$  and  $b = C_1$ .

$$\begin{pmatrix} \sum Y(i) \times X(i) \\ \sum Y(i) \end{pmatrix} = \begin{pmatrix} \sum X^2(i) & \sum X(i) \\ \sum X(i) & n \end{pmatrix} \begin{pmatrix} a \\ b \end{pmatrix} \quad (8)$$

$$a = K_1 = \{n \times \sum Y(i) \times X(i) - \sum X(i) \times Y(i)\} / DET \quad (9)$$

$$b = C_1 = \{-\sum X(i) \times \sum Y(i) \times X(i) + \sum X^2(i) \times \sum Y(i)\} / DET \quad (10)$$

Cylinder pressure,  $P$ , following correction can therefore be expressed as Eq. (11).

$$P = P' \times K_1 + C_1 \quad (11)$$

#### 4. Results of Vehicle Tests

Figures 10 and 11 show the 100 cycle combustion waveform at a vehicle speed of 50 mph. The engine speed was 1500 rpm, and the pressure in the intake cylinders was 43 kPa. Figure 10 shows results for a sensor with a sensitivity of 2000 pC/MPa, and Fig. 11 shows results for a sensor with a sensitivity of 380 pC/MPa. The calculated  $P_{modelk}$  displays the same values as the measured pressure, but because the sensitivity of the 380 pC/MPa sensor is low, the obtained cylinder pressure is low.

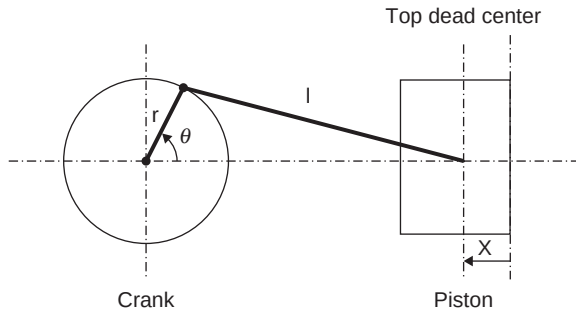


Fig. 8 Crank angle and piston geometry

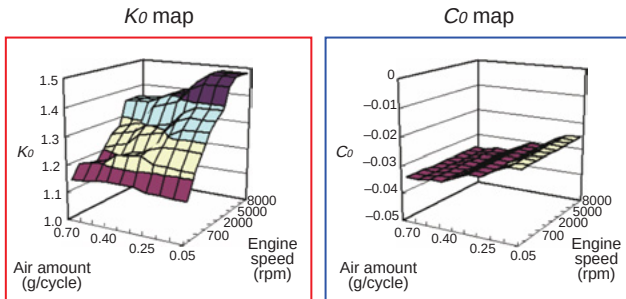


Fig. 9  $K_0$ ,  $C_0$  mapping result

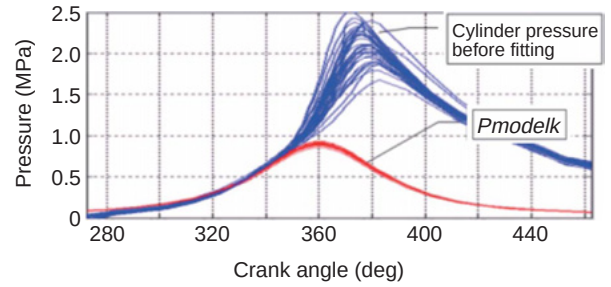


Fig. 10 Cylinder pressure before fitting (Sensor sensitivity: 2000 pC/MPa)

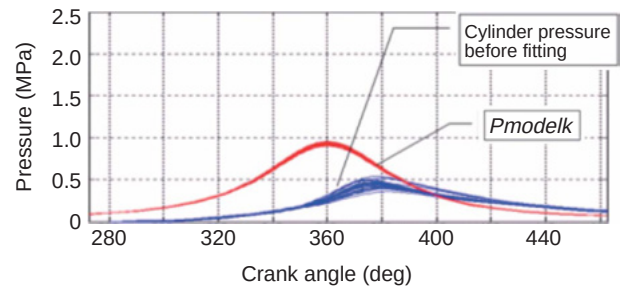


Fig. 11 Cylinder pressure before fitting (Sensor sensitivity: 380 pC/MPa)

Figures 12 and 13 show results following correction, when the waveform during the compression stroke is identified with the model motoring cylinder pressure. Before identification, there are variations between the pressure measured by the sensor during the compression stroke and the model pressure, but following identification, the waveform during the compression stroke matches the model waveform. In addition, the output of the 380 pC/MPa sensor was increased using the correction coefficient  $K_1$  to match the output of the 2000 pC/MPa sensor. The range for identification was set at between 284 and 340 deg after intake top dead center.

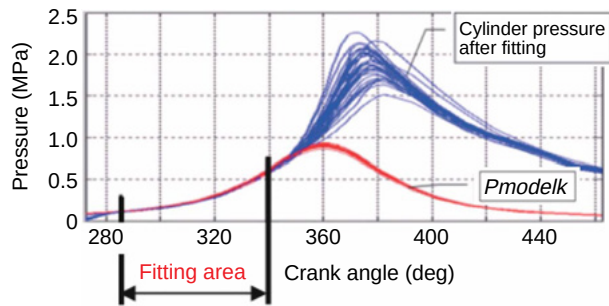


Fig. 12 Cylinder pressure after fitting  
(Sensor sensitivity: 2000 pC/MPa)

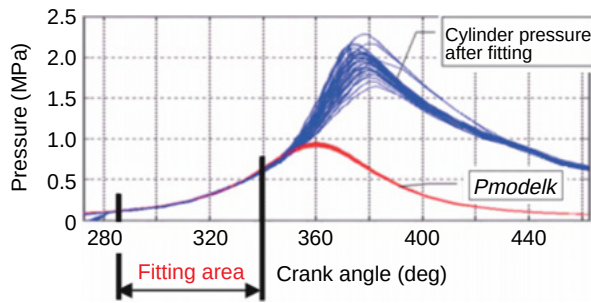


Fig. 13 Cylinder pressure after fitting  
(Sensor sensitivity: 380 pC/MPa)

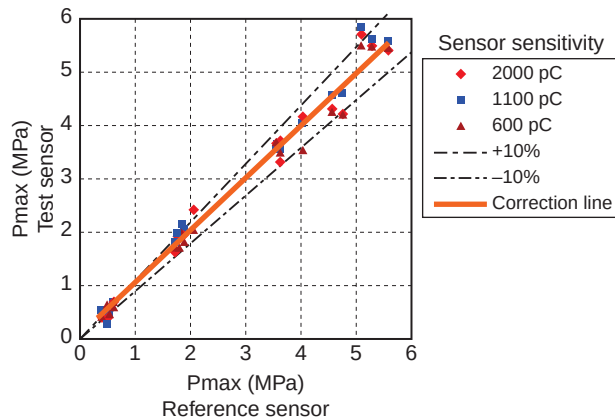


Fig. 14 Pmax comparison between test sensor and reference sensor

Real time correction was able to be performed despite differences in vehicle operating conditions and the sensitivity of sensors. Figure 14 shows a comparison of Pmax (maximum cylinder pressure) obtained using the benchmark sensor and the system discussed here, using sensors with sensitivities of 600, 1100, and 2000 pC/MPa at engine speeds between 500 and 4000 rpm and engine loads varying between an intake cylinder pressure of 20 kPa and WOT. The new system produced figures with only a 10% degree of error against the benchmark sensor.

## 5. Example of Application to Misfire Detection

In conventional mass production vehicles, misfires are detected on the basis of changes in the angular velocity of the crank. However, in engines with a large number of cylinders and engines with compression strokes that are unequally spaced in time, in which the combustion period of any cylinder overlaps with the combustion period of other cylinders, setting misfire detection criteria for this method is challenging, and requires considerable man hours. Because the developed system enables measurement of pressure for combustion in each cylinder, no error is produced by external disturbances, thus enabling stable detection of misfires. As Fig. 15 shows, cylinder pressure increases as combustion proceeds during normal combustion, but matches the model motoring cylinder pressure when misfires occur.

This characteristic can be exploited to enable the state of combustion to be monitored. Misfires can be judged by integrating the ratio between the integrals of the cylinder pressure waveform during combustion and the model motoring cylinder pressure waveform [Eq. (12)]. During combustion, the ratio is higher than 1. If a misfire occurs, the cylinder pressure matches the model motoring cylinder pressure, and the ratio becomes 1.

$$\text{Integral ratio in combustion} = \int \frac{P(\text{Cylinder pressure})}{P(P_{\text{modelk}})} \quad (12)$$

This enables complete misfire detection at low and high temperatures and at high altitudes. These results have

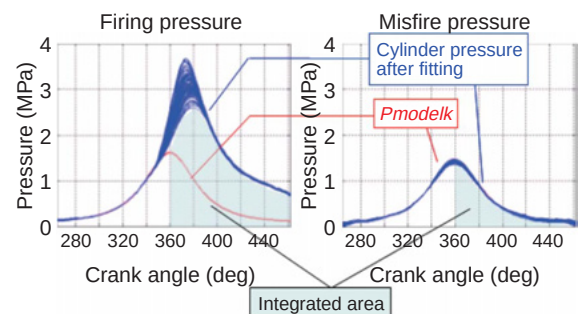


Fig. 15 Difference between firing pressure and misfire pressure

demonstrated the viability of this low-cost sensor for misfire detection in an actual vehicle.

## 6. Conclusion

A system enabling real time measurement of cylinder pressure has been developed using a polycrystalline piezoelectric element that is able to be mass produced. The system displays good prospects as a technology enabling mass production of cylinder pressure sensors.

The following are the salient points of this research project.

- (1) The variation in the sensitivity of the sensor was elucidated, and a method of automatic correction of changes in sensitivity using adaptive calculation was developed.
- (2) Operating tests using a mass production vehicle indicated that the cylinder pressure measured in real time could be used as a simple and accurate method of detecting misfires.

It will be necessary to increase the accuracy of the sensor in order to expand its range of application to other control systems, and thus also to perform additional research.

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