

Development of Cylinder Pressure Sensor Integrated with Direct Injector

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ABSTRACT

Polycrystalline piezo-electric element-type cylinder pressure sensors developed thus far require correction of the output characteristics due to pyroelectricity and other factors. This type of sensors also made it necessary to use plug clamp-type sensors, which had a large influence on engine layout.

This issue was addressed by integrating a single crystal piezo-electric element-type cylinder pressure sensor with a direct injector, and this paper introduces the effects and characteristics of this new sensor. Use of an integrated sensor and injector structure provided commonality with existing parts and enabled easy installation in turbocharged engines with direct injection that are expected to become widespread in the future. In addition, with regards to cylinder pressure detectability, the use of single crystal piezo-electric elements with good temperature characteristics achieved a detection accuracy of $\pm 3\%$ compared to the reference sensor (Kistler (6052B)). Furthermore, the knocking waveform detectability was also confirmed to be the same level as that of the reference sensor.

1. Introduction

Recently in Japan, technologies that enhance fuel economy are being mass produced such as small cars equipped with high-efficiency internal combustion engines as opposed to electric cars and hybrid cars, and compact cars equipped with idling stop technology. In addition, technologies that enhance fuel economy centering on increasing combustion efficiency are gaining attention in Europe and other regions, as seen by the increasing popularity of down-sized turbocharged engines and research on Cooled-EGR and Homogeneous Charge Compression Ignition (HCCI) combustion.

Gasoline engines are also evolving from port injection types to direct injection types that spray fuel directly into the combustion chamber, and combustion control that was formerly a challenge using only the combustion chamber shape and ignition timing control has also become possible. As a result, more parameters are being used, and there are demands for even more detailed control. Various companies are developing cylinder pressure sensors to meet these demands, but so far these sensors have been mass produced in only some gasoline and diesel engines⁽¹⁾⁻⁽⁷⁾.

To meet these requests for complex and detailed

control and apply combustion control technology to mass production, research has been conducted over many years to develop methods that combine real-time measurement of gasoline engine cylinder pressures with CPU capable of executing heat and efficiency calculations at high speed. These efforts include the research and development of a plug clamp-type cylinder pressure sensor^{(8), (9)}. This sensor featured a structure that enabled mounting without affecting the valve structure, but assembly limitations required changes to the plug hole and the head cover.

In addition, the sensor used polycrystalline piezo-electric elements, so there were the issues of varying output sensitivity due to the temperature characteristics and output drift due to pyroelectricity, which required special software⁽⁸⁾. These issues were addressed by developing a new sensor. The details are described below.

2. Development of Cylinder Pressure Sensor

2.1. Features of the New Cylinder Pressure Sensor

The use of direct injectors in gasoline engines has increased in recent years. As shown in Fig. 1, the new sensor locates ultra-compact single crystal elements around the fuel injection port at the tip of the direct injector.

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The new cylinder pressure sensor is integrated with the injector, so there is no need for special changes to the hardware and head layout. In addition, the new sensor has the characteristic that the element temperature can be maintained at 150°C or less by the cooling effect of the fuel sprayed from the injector, so there are no thermal issues. Furthermore, there is also no change to the shaft seal structure, making it a highly versatile sensor. On the other hand, conventional plug clamp-type sensors detect the combustion pressure as head strain, so they are subject to the influences of intake valve and exhaust valve closing. However, the new cylinder pressure sensor directly detects the cylinder pressure, so it is not subject to these influences.

Figure 2 shows the sensor structure. The basic structure has piezo-electric elements assembled in a ring shape at the tip of the injector. One of the piezo-electric element electrodes is connected externally via electrode material coated onto the pressure transmission location.

The piezo-electric elements use single crystal piezo-electric elements with good temperature characteristics. These piezo-electric elements can accurately detect the cylinder pressure without the need to correct sensitivity due to varying temperature characteristics or to correct drift due to pyroelectricity.

2.2. Characteristics of the Piezo-electric Elements

The piezo-electric elements use langatate single crystals. As shown in Fig. 3, the crystallization structure of a langatate single crystal is that of a trigonal crystal belonging to the space group P321. It is a single crystal without pyroelectricity that exhibits only piezo-electricity,

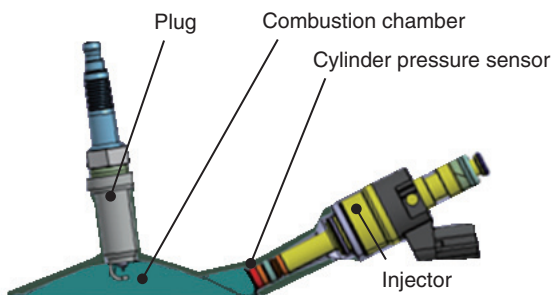


Fig. 1 Installation of injector with cylinder pressure sensor

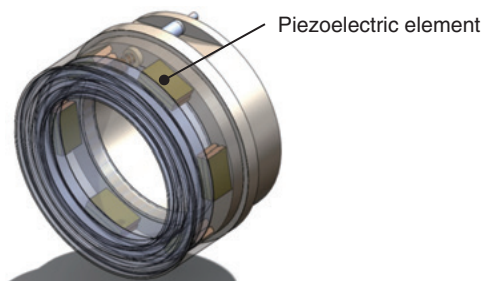


Fig. 2 Cylinder pressure sensor structure

and comprises the four different cation sites A to D. The compositional formula is expressed as $A_3BC_3D_2O_{14}$, and typical langatate is expressed by the chemical formula $La_3Ga_{5.5}Ta_{0.5}O_{14}$.

Polycrystalline piezo-electric elements are molded from powder, and polarization does not occur in the firing stage. A piezo-electric crystal with the entire polycrystalline structure polarized in a single direction is obtained by externally applying high voltage under high temperatures of the Curie point or more to induce unidirectional polarization and forcibly unify the self-canceling spontaneous polarization. Piezo-electric elements manufactured by this method return to the original polarization direction and lose piezo-electricity due to repeated pressure amplitude, and in particular when pressure amplitude is repeated under high temperatures or near the Curie point.

In contrast, langatate piezo-electric single crystals have spontaneous polarization in a single direction from the end of the growth stage, so polarization treatment is not required, and there is no Curie point up to the melting point, so the structure also does not change. In addition, langatate piezo-electric single crystals are disordered crystals that experience differences in melt composition and crystal growth composition during crystal growth, but they can be grown by melt solidification such as the Cz method, so larger crystals are easier to obtain compared to AlN or GaPO₄. Furthermore, the lack of a Curie point up to the melting point is also a reason for the easier growth and stability. For these reasons, langatate single crystals have good stability and the piezo-electric constant has a low temperature dependency over a wide temperature range from low to high temperatures, which gives them good characteristics as piezo-electric elements for cylinder pressure sensors (Table 1).

The sensor structure transmits pressure from the tip of the sensor facing the combustion chamber to the elements, and extracts the stress generated on the sensor as the output. Therefore, the target sensitivity was set at 50 pC/Mpa, based on an S/N ratio that does not affect the combustion parameter calculations, and the sensor layout and structure

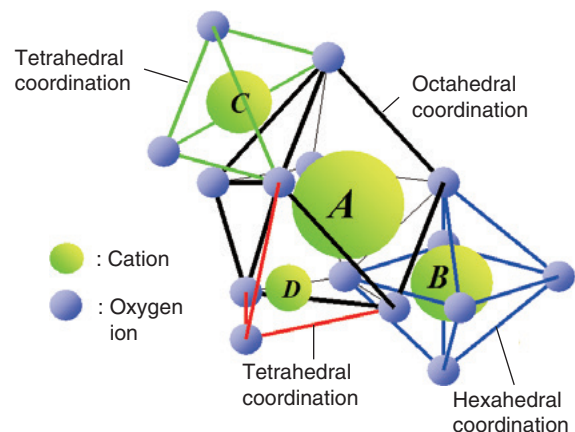


Fig. 3 Langatate crystallization structure

Table 1 Piezoelectric element comparison

		Single crystal		Polycrystalline	
		La _{0.5} Ga _{0.5} Ta _{0.5} O ₁₄ langatate	SiO ₂ quartz	PbTiO ₃ lead titanate	PbNb ₂ O ₆ lead niobate
Performance characteristic	Piezoelectric constant (pC/N)	7.5	2.5	60	80
	Pyroelectricity (pC/°C)	0	10	20000	15000
	Temperature characteristics (%/°C)	0.5<	0.1	0.4	0.3
Degradation characteristic	Curie temperature (°C)	—	570	490	570
	Piezoelectric property degradation temperature (°C)	—	350	300	350
	Breaking strength (MPa)	800	400	500	300
	Piezoelectric property degradation pressure (MPa)	800	300	400	200

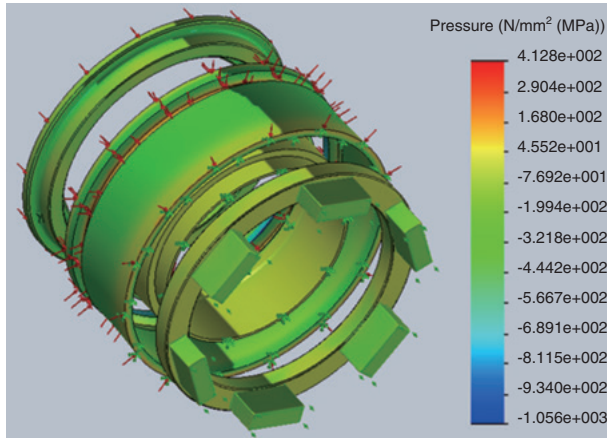


Fig. 4 Sensor stress simulation result

were optimized using simulations. Figure 4 shows the output simulation results for the cylinder pressure sensor. When 15 MPa was applied in the output simulation, the load applied to the piezo-electric element was 103 N. When piezo-electric elements are manufactured using the longitudinal piezo-electric effect Q_x of langatate, the discrete crystal output is approximately 7 pC/N.

The electric charge generated at this time is 721 pC, and the sensor output is estimated to be 48 pC/MPa.

An actual cylinder pressure sensor was manufactured and the output was confirmed to be 50 pC/MPa. This is a difference of 2 pC/MPa from the simulation, which achieved the target performance.

3. Development of Injector Integrated with Cylinder Pressure Sensor

3.1. Injector Structure

To enable mounting of the sensor in the tip of the injector without changing the outer diameter, the valve seat needs to be able to fit inside the ring-shaped sensor. This was achieved by reducing the valve seat and body wall thickness. Structural analysis simulations were used to optimize the valve seat and body to obtain the same strength

as that of the base injector.

Figure 5 shows the structure of the developed injector. The external dimensions are the same as those of the base injector, and the pressure signal cable is wired from the sensor mounted on the tip of the injector, through the inside of the seal ring, to the connector side. The pressure signal cable uses a thin coaxial cable in consideration of electrical noise.

The valve seat inside diameter greatly influences the injector flow rate characteristics. Therefore, simulations were performed and the valve seat inside diameter was set so that the valve seat deformation was the same as that of the base injector or less. Using the valve seat outside diameter D as the variable, the outside diameter was set to suppress the deformation Δd of the valve seat inside diameter d after press-fitting to the same as that of the base injector or less, as shown in Fig. 6.

Stress due to the fuel pressure concentrates on the body undergroove, which is used to lead the pressure signal cable. Figure 7 shows the relationship between the undergroove wall thickness t and the stress. This development set the undergroove wall thickness based on these results, achieving sufficient body strength relative to the stress generated by the fuel pressure.

Next, the methods used to ease assembly and help

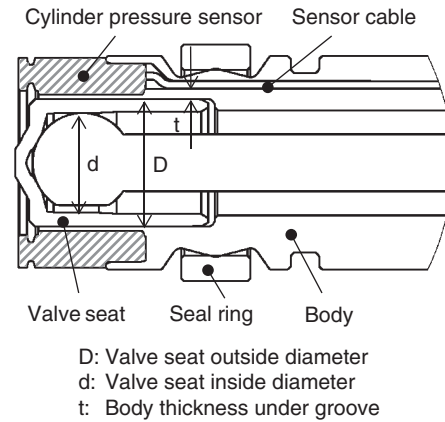


Fig. 5 Injector structure

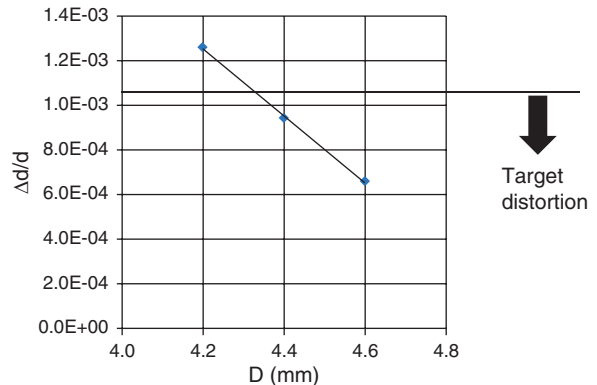


Fig. 6 Valve seat diameter simulation result

prevent broken cables are described. As shown in Fig. 8, the structure leads out the pressure signal cable via a coupler, so a 3-pin-type connector was used. The structure leads out the sensor signal from the center terminal.

The method of dealing with the injector drive noise is as follows. Magnetic field analysis simulation was performed, and the magnetic path structure was determined that minimizes the magnetic field strength. Figure 9 shows the magnetic field analysis simulation result. This figure shows that the housing outside diameter should be increased to reduce the effects of the magnetic field generated by injector operation. This development set the maximum housing outside diameter D_h in accordance with this simulation.

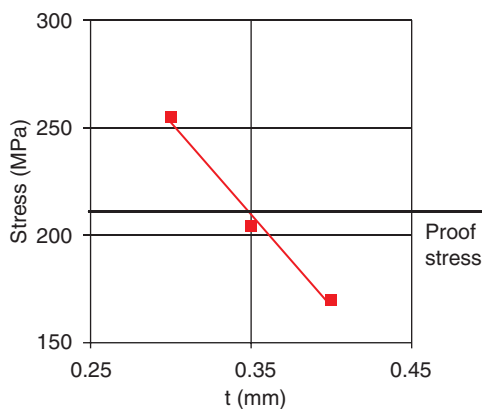


Fig. 7 Body stress simulation result

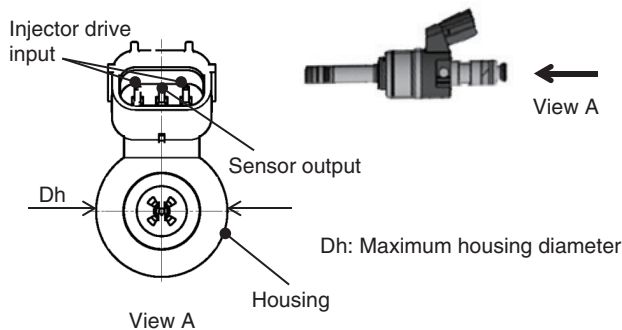


Fig. 8 Signal connector layout

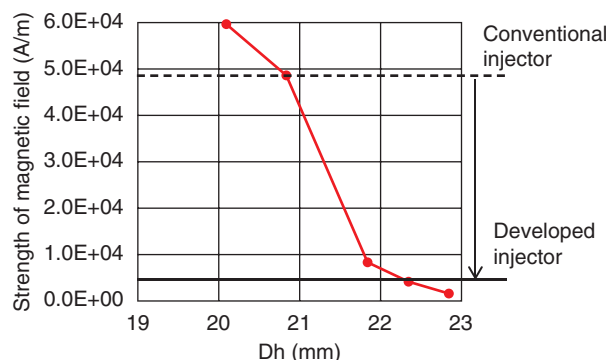


Fig. 9 Magnetic field simulation result

3.2. Evaluation of Injector Performance

The injector flow rate characteristics were verified to confirm the effects of sensor installation. As shown in Fig. 10, the flow rate characteristics proved to be the same as those of the conventional injector.

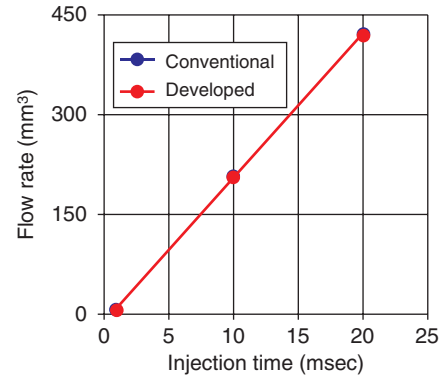


Fig. 10 Flow rate characteristics

4. Verification Results Using an Actual Engine

The cylinder pressure detecting performance was evaluated by comparison with the reference sensor (Kistler (6052B)) using a test bench. The engine used was an inline-four 2000 cm³ engine, and comparison was performed under the conditions of 2000 rpm and 180 Nm.

Figure 11 compares the cylinder pressure waveforms of the reference sensor and the new cylinder pressure sensor, and Fig. 12 shows the correlation with the reference sensor. The developed sensor obtained output results within $\pm 3\%$ of the reference sensor.

In addition, the ability to detect knocking waveforms near 10 kHz is an important factor as a cylinder pressure sensor. Therefore, the knocking waveform under conditions of 1500 rpm and a medium load was compared with that of the reference sensor. As shown in Fig. 13, the developed sensor obtained the same pressure as that of the reference sensor.

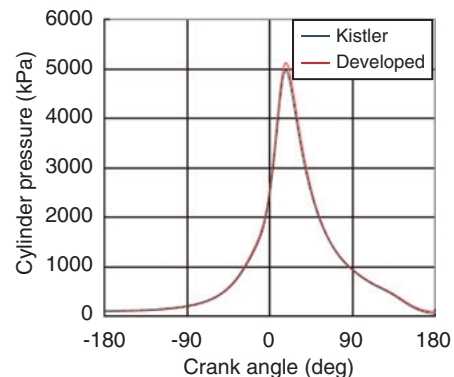


Fig. 11 Cylinder pressure measurement result

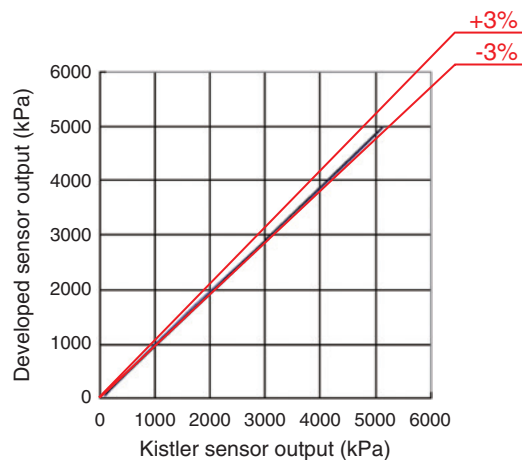


Fig. 12 Cylinder pressure correlation result

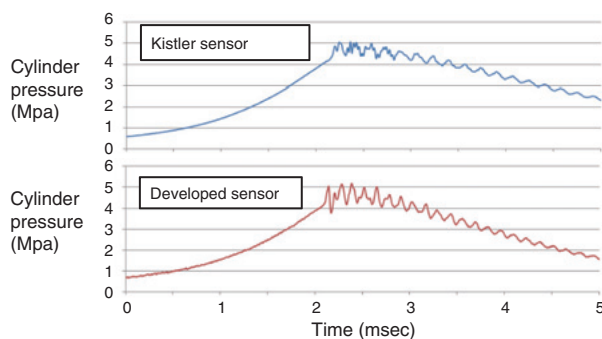


Fig. 13 Cylinder pressures with knocking

5. Conclusion

Ultra-compact single crystal piezo-electric elements were arranged around the fuel injection port of a direct injector. This enabled maintaining the element temperature at 150°C or less due to the active cooling effect of the fuel, thus realizing a lower temperature environment than the conventional technology. In addition, locating the sensor in close proximity to the combustion chamber also enabled detection of knocking. At the same time, the cylinder pressure sensor could be integrated with the direct injector without changing the injector hardware configuration.

- (1) The developed injector can be contained within the same dimensions as the conventional injector, and can be mounted without any change to the engine hardware.
- (2) The developed injector with integrated cylinder pressure sensor was confirmed to have no effect on the flow rate characteristics compared to the conventional direct injector.
- (3) The cylinder pressure detection accuracy was confirmed to be within $\pm 3\%$ of that of the reference sensor, and the knocking pressure could also be detected to the same degree as the reference sensor.

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