

Measurement of Piston Skirt Oil-film Pressure when Piston Slap Noise Occurs

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ABSTRACT

A small thin-film pressure sensor that does not affect the piston skirt surface geometry, stiffness, and mass was directly deposited onto the piston skirt surface by physical vapor deposition, and the oil-film pressure on the skirt surface which is closely related to the cylinder liner excitation force when piston slap noise occurs was measured. The oil-film pressure corresponding to the cylinder liner acceleration, which is an indicator of piston slap noise, was measured in an engine under running condition, and the accuracy of this measurement was confirmed. It was also possible to measure the change in the oil-film pressure distribution on the piston skirt surface corresponding to changes in engine speed and the piston pin offset. The difference of the oil-film pressure on the piston skirt surface when the piston collides with the cylinder liner, which was not possible to explain from cylinder liner acceleration alone, allowed the mechanism where the piston secondary motion differs to be identified. As a result, the accuracy of the piston secondary motion simulation was enhanced, enabling effective measures against piston slap noise to be studied.

1. Introduction

Engines have been required to be compact, lightweight, high-output, highly fuel efficient and capable of producing lower levels of exhaust emissions and pollution in recent years. In addition, quietness is another strong commercial requirement for contemporary engines. To meet these performance requirements the reduction of piston slap noise, brought about by adjusting the piston offset and modifying the shape of the piston skirt, as well as the achievement of weight savings, durability, and friction reductions are design targets during piston development.

Along with the progress of continuing simulation technology, it is becoming possible to predict the piston secondary motion and the distribution of oil-film pressure on the piston skirt surface when piston slap noise occurs. However, the predictive accuracy of the simulation is insufficient and the development time required for piston development cannot yet be reduced, so there are demands to enhance the predictive accuracy.

Accordingly, it is necessary to measure the time career transition of the oil-film pressure distribution on the piston skirt surface, which is particularly closely related to the piston excitation force when piston slap noise occurs, and thereby clarify the mechanism of piston slap noise.

In this paper, the influential factors that would enhance the accuracy of the piston secondary motion were determined, which will contribute to the development efficiency. In the measurement, a compact thin-film pressure sensor was newly used in an attempt to directly measure oil-film pressure on the piston skirt surface when piston slap noise occurs.

2. Method of Measuring Oil-film Pressure on the Piston Skirt Surface

2.1. Piston Slap Noise and Oil-film Pressure Measurement

Piston slap noise occurring at the anti-thrust side was studied by measuring the oil-film pressure on the piston

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skirt surface. Mainly because of the increase and decrease of the inertial force of the reciprocating parts and in-cylinder pressure, the piston moves abruptly from the thrust side to the anti-thrust side in the top dead center vicinity of the compression and combustion strokes. At the same time, the moment generated around the piston pin makes the piston rotate, and the anti-thrust side skirt surface collides with the cylinder liner. Piston slap noise is considered to occur in this way⁽¹⁾. However, in an actual running engine, this behavior occurs in a short time, so when the cylinder liner acceleration was measured, the relationship with the piston secondary motion was unclear, and it was difficult to determine the extent to which the lateral motion and rotational motion of the piston contributed to the cylinder liner acceleration.

In order to clarify the mechanism of this piston secondary motion, it is necessary to measure the distribution of the oil-film pressure on the piston skirt surface. However, it is not possible to use large sensors that affect the mass of the reciprocating parts, or to use a measurement method that causes the piston skirt stiffness or the skirt surface properties to change.

Therefore, a sensor that can directly measure the oil-film pressure distribution on the skirt surface without affecting the piston mass, skirt surface stiffness, or shape was used.

2.2. Outline of Measurement Method

To measure the oil-film pressure distribution on the piston skirt surface, a thin-film pressure sensor that can be deposited directly on the surface of a sliding part of the engine was used. This sensor was developed to measure the oil-film pressure distribution on the main bearings of an actual running engine⁽²⁾, and has already been used to measure the oil-film pressure distribution on the piston pin boss and connecting rod big-end bearing^{(3) - (5)}. Also during the research on the engine plain bearings⁽⁶⁾, this sensor has been used to verify the oil-film pressure distribution using a component jig tester. However, this is the first time that a thin-film pressure sensor has been used on the piston skirt, which is a representative reciprocating part of an actual running engine.

2.3. Sensor Construction

The pressure sensing part of the thin-film pressure sensor consists of a thin-film resistor deposited directly on the sensing part by means of physical vapor deposition. This sensor does not need mounting holes or an oil-leading hole for measurement, and can be installed in a shape that corresponds to the curvature of the sliding part. It therefore has the merit of exerting relatively little effect that would cause a shape change, stiffness reduction, or mass increase of the measurement object.

The thin-film pressure sensor has the shape shown in Fig. 1, and can measure pressure in as small an area of

Table 1 Alloy composition of sensors [wt%]

	Cu	Mn	Ni
Cu-Mn-Ni alloy	87.8	8.75	3.45

about 1 mm or less. As shown in Fig. 2, the sensor film consists of an intermediate film to increase bonding strength, an isolation film, pressure sensing film, lead film, and protection film on the surface of the piston, which is an electrical conductor. The total film thickness is 12.6 μm . The depositing area on the piston skirt surface used in this measurement was polished by an amount equal to the total film thickness, prior to the depositing operation, since the piston diameter had to be maintained the same as that of an actual engine after the sensor has been deposited.

2.4. Sensor Material and Pressure Characteristics

For the pressure sensing material, a copper, manganese and nickel (Cu-Mn-Ni) alloy was used for measurement of the oil-film pressure distribution on the main bearings and the connecting rod big end in an actual running engine^{(2) - (4)}. Table 1 shows the composition of the sensor alloy.

Figure 3 shows an example of the output characteristics of the sensor fabricated from this material with respect to the pressure. High linearity and low hysteresis were obtained between the 0 and 10 MPa measurement range.

2.5. Measurement Position

Figure 4 shows the calculation results of the oil-film pressure distribution on the piston skirt surface when piston slap noise occurred at different piston pin offsets

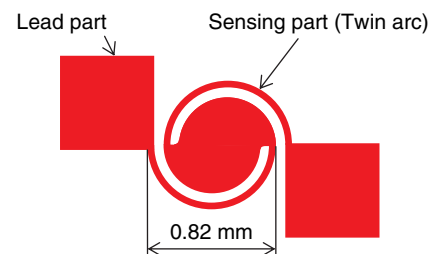


Fig. 1 Shape of thin-film sensor (Plain view)

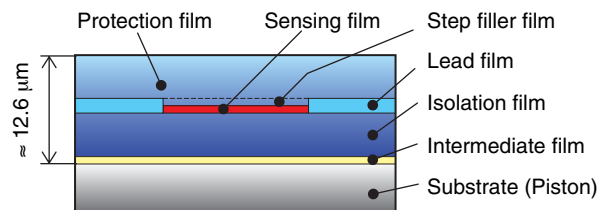


Fig. 2 Structure of thin-film sensor (Cross section)

obtained by using the existing piston secondary motion simulation. Based on these results and experience obtained during conventional development, a total of three thin-film sensors were deposited. One was deposited on the anti-thrust side piston skirt at the same position as the center of the piston pin hole, and the other two were deposited at progressive intervals of 4 mm going upward from the position of the first sensor as shown in Fig. 5.

2.6. Test Engine and Measurement Apparatus

Table 2 shows the basic specifications of the test engine.

Measurement was performed on the piston in cylinder

Table 2 Engine specifications

Engine type	Water-cooled, DOHC, 4-stroke 16 valves, In-line 4-cylinder, gasoline		
Bore × Stroke	[mm]	86.0 × 86.0	
Displacement	[cm ³]	1998	
Compression ratio		9.8 : 1	
Max. power	[kW / (r/min)]	118 / 6500	
Max. torque	[N·m / (r/min)]	191 / 4000	
Piston pin offset	[mm]	0.8 (Standard)	1.3
Cylinder offset	[mm]	0.0	

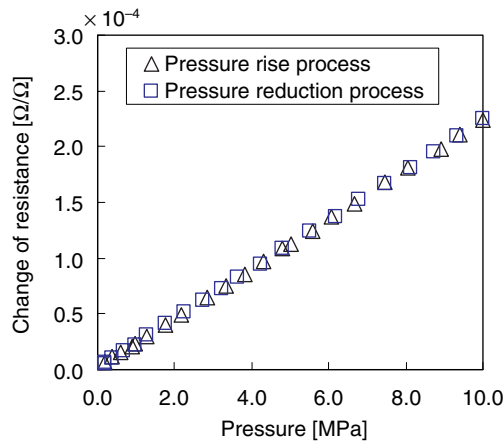


Fig. 3 Pressure-resistance characteristics

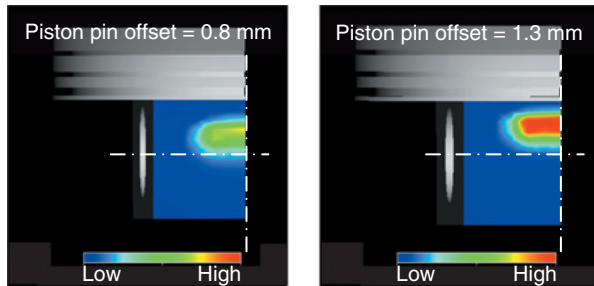


Fig. 4 Simulation results of oil-film pressure distribution on anti-thrust side skirt

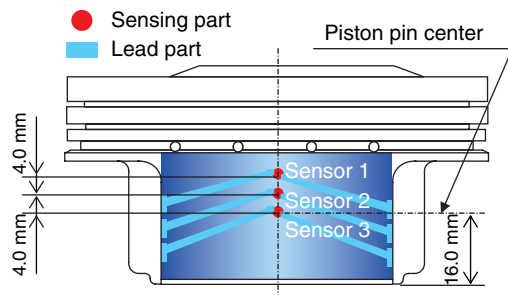


Fig. 5 Thin-film pressure sensors on anti-thrust side skirt

number 3. The linkage shown in Fig. 6 was used to run the wiring from the sensor signal terminal mounted on the piston to the outside of the engine. The linkage has three joints extending from the connecting rod big end. The wiring lead from the three thin-film pressure sensors is indicated by the arrows joining a point on the piston skirt surface to the connecting rod and linkage.

The thin-film pressure sensors are metallic resistance

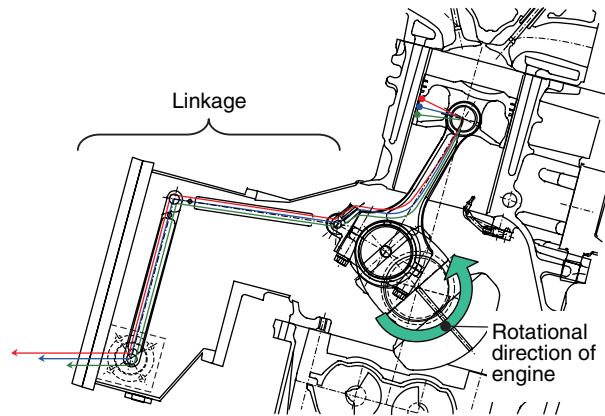


Fig. 6 Linkage and wiring from thin-film sensors

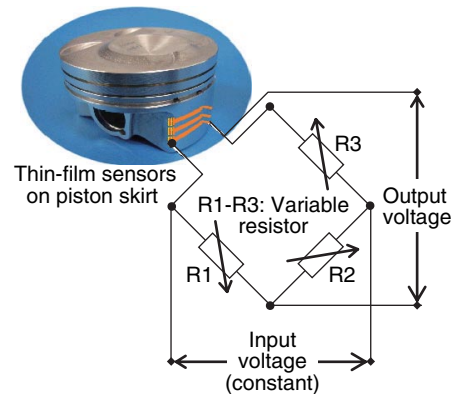


Fig. 7 Measurement circuit (Wheatstone bridge)

elements. The sensor resistance varies slightly according to the pressure applied to it. By incorporating each of these thin-film pressure sensors in one arm of the Wheatstone bridge circuit shown in Fig. 7, a minute voltage is generated between the terminals in the Wheatstone bridge circuit. This minute voltage output is amplified by a strain amplifier and measured.

3. Measurement Results and Considerations

3.1. Relation Between the Oil-film Pressure on the Piston Skirt Surface and Cylinder Liner Acceleration

The running conditions of the test engine were: engine coolant temperature 0 °C, firing, no load, mainly from 3000 r/min to 4000 r/min. When the piston pin offset is changed from 0.8 mm to 1.3 mm to the thrust side, piston slap noise is occurred at the anti-thrust side.

Accordingly, as shown in Fig. 8, a single axis acceleration sensor was installed in the normal line with respect to the circumference of the cylinder liner inside the water jacket on the outer wall of the cylinder. The measured value of the cylinder liner acceleration was

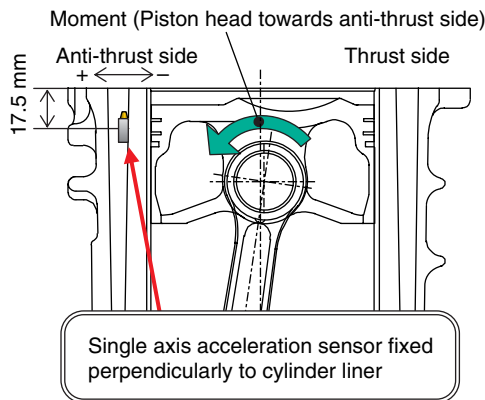


Fig. 8 Location of acceleration sensor

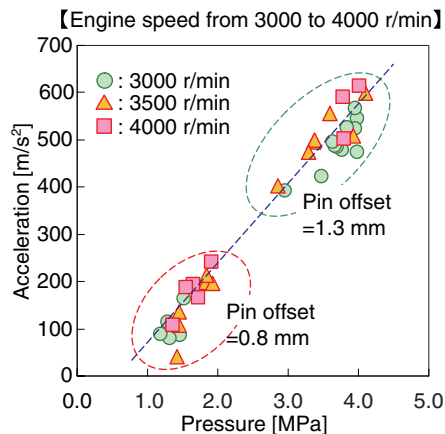


Fig. 9 Pressure measured by sensor 1 versus cylinder liner acceleration at two different piston pin offsets

treated as an objective value of the piston excitation force when slap noise is occurred, and correlation between this value and the measured value of the oil-film pressure on the piston skirt surface was investigated.

Figure 9 shows the measured values of the anti-thrust side cylinder liner acceleration sensor versus the measured values of the output from thin-film pressure sensor 1 on the anti-thrust side piston skirt surface when piston slap noise occurred under the above-mentioned running conditions.

In the figure, the area surrounded by the lower broken line represents the results for a piston offset of 0.8 mm, and the area surrounded by the upper broken line represents the results for a piston offset of 1.3 mm. The straight broken line is an approximation straight line based on the method of least squares of both results. The results obtained for the same engine speed are indicated by the same symbols.

Even taking random variations that occur due to fluctuations in combustion pressure and piston secondary motion from one cycle to another, and a slightly different contact point from the sensor position into consideration, a high proportional correlation coefficient, $R^2 = 0.980$, was obtained between the measured value of thin-film pressure sensor 1 on the anti-thrust side piston skirt surface, and the cylinder liner acceleration when slap noise occurred. Consequently, it is considered that the measured value obtained from the thin-film pressure sensor when slap noise occurs represents the piston excitation force accurately, indicating the effectiveness of the measurement method using the thin-film pressure sensor.

3.2. Comparison of Oil-film Pressure on the Piston Skirt Surface at Different Engine Speeds

Figure 10 (a) shows the measured combustion pressure values, Fig. 10 (b) shows the measured cylinder liner acceleration values on the anti-thrust side, and Fig. 10 (c) shows the measured oil-film pressure values on the anti-thrust side of the piston skirt surface. Figures 10 (d) and 10 (e) show the calculated piston side force values and the calculated piston rotational moment values around the piston pin center, obtained by using a simple mechanical model. The vertical broken line in each figure is the crank angle at which the cylinder liner acceleration occurs.

Figures 10 (b) and 10 (c) show that at 2000 r/min the cylinder liner acceleration is small, and the output from the thin-film pressure sensor on the piston skirt surface lags in phase with respect to the cylinder liner acceleration output. On the other hand, at 3500 r/min there is no phase difference between the thin-film pressure sensor output and crank angle at which cylinder liner acceleration occurs. However, the cylinder liner acceleration is large, and the three thin-film pressure sensors arranged in the vertical direction of the cylinder liner show a sequential reduction of output values from

sensors 1 to 2 to 3, as in the case of 2000 r/min.

In Fig. 10 (d), the calculated value of the side force at the crank angle where the cylinder liner acceleration occurs is roughly 0 N at 2000 r/min, but is around -700 N at 3500 r/min, and a force acts on the piston causing it

to move from the anti-thrust side to the thrust side.

In addition, in Fig. 10 (e), the calculated value of the rotational moment around the piston pin indicates a weak moment acts on the piston in the anti-thrust direction at 2000 r/min, but a strong moment acts in the anti-thrust

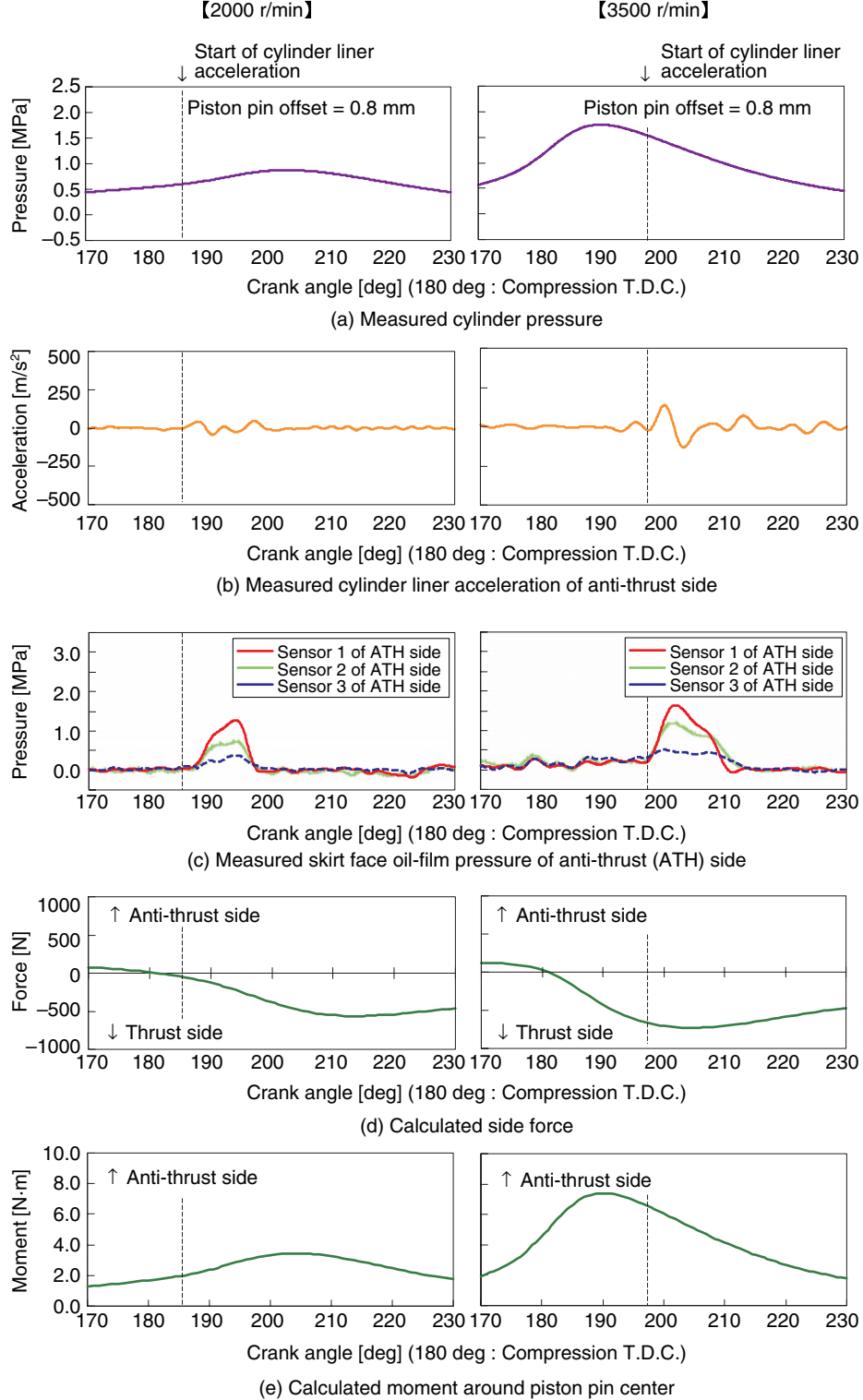


Fig. 10 Experimental and calculation results for different engine speeds

direction (direction causing the piston head to be pushed to the anti-thrust side) at 3500 r/min.

Based on the above results, Figs. 11 and 12 show the piston secondary motion at 2000 r/min and 3500 r/min, respectively.

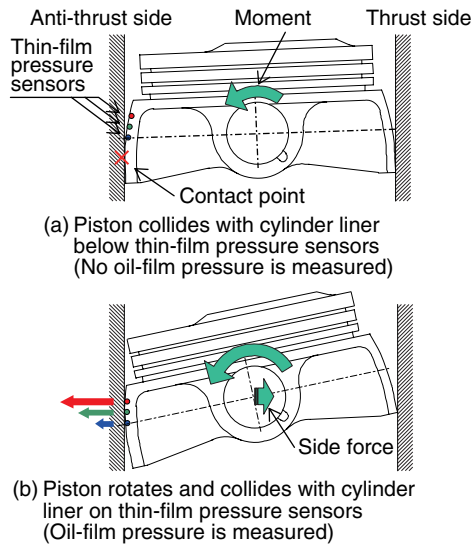


Fig. 11 Piston secondary motion at 2000 r/min

It is considered that the following occurred at 2000 r/min: Before the cylinder liner acceleration occurred, the piston was pushed to the anti-thrust side by a small side force. Subsequently, as soon as the effect of the side force disappeared, the piston, which had been subjected to the weak rotational moment around the piston pin, contacted the cylinder liner at a point below the thin-film pressure sensor, as shown in Fig. 11 (a), and only the cylinder liner acceleration occurred. After this, as shown in Fig. 11 (b), the moment around the anti-thrust continued to increase while the piston was separating from the cylinder liner, and the piston re-contacted the cylinder liner at the

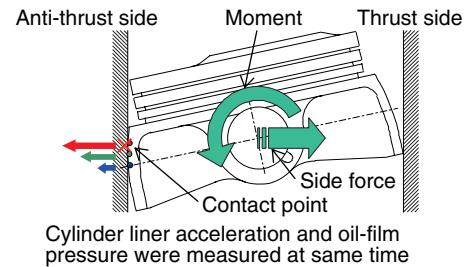


Fig. 12 Piston secondary motion at 3500 r/min

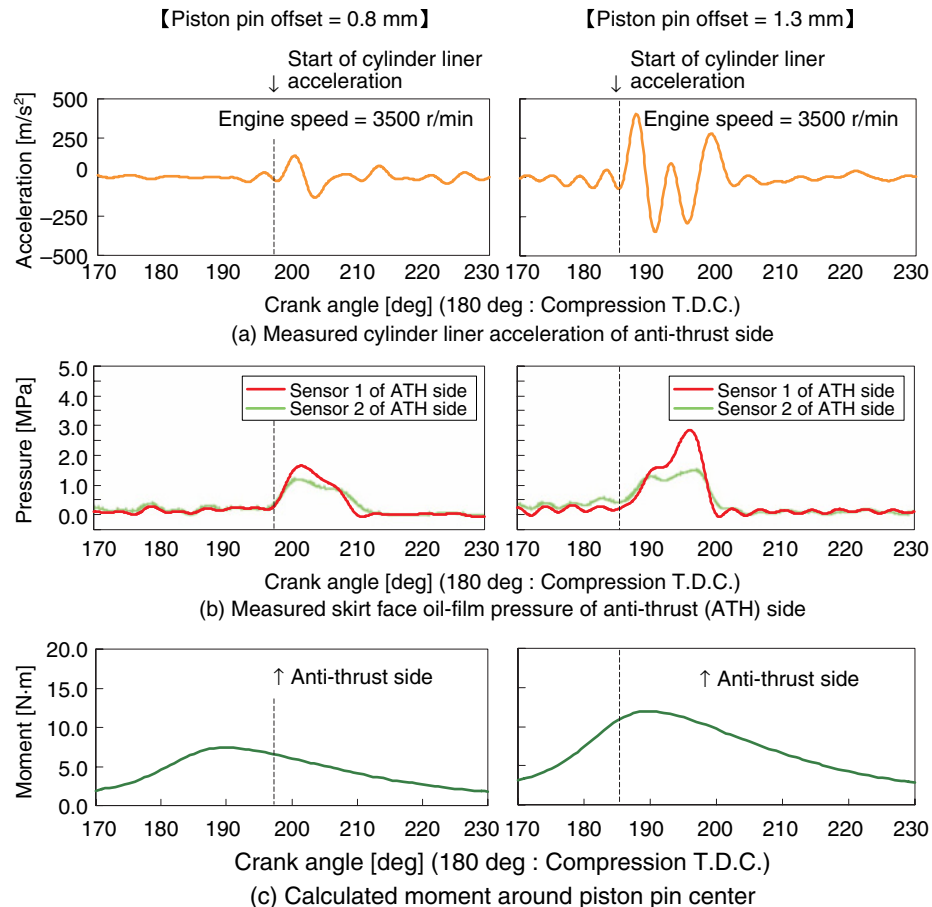


Fig. 13 Experimental and calculation results for different piston pin offsets at 3500 r/min

thin-film pressure sensor location. As a result, a phase of the oil-film pressure sensor output was delayed with respect to the crank angle at which the cylinder liner acceleration occurred.

Likewise, it is considered that the following occurred at 3500 r/min: The piston was pushed to the thrust side as shown in Fig. 12, and a clearance approximately equal to the piston clearance was formed at the anti-thrust side. In this condition, a strong moment around the piston pin acted on the piston in the anti-thrust direction. At this time, the piston rotated in the anti-thrust direction about the piston pin and contacted the cylinder liner in the vicinity of thin-film pressure sensor 1, located at the highest point. Consequently, the cylinder liner acceleration and oil-film pressure on the skirt surface were both large, and no phase difference occurred.

3.3. Comparison of the Oil-film Pressure on the Skirt Surface due to the Piston Pin Offset Difference at the Equivalent Combustion Pressure

Figure 13 (a) shows the measured values of the anti-thrust side cylinder liner acceleration, and Fig. 13 (b) shows the measured values of the thin-film pressure sensor on the piston skirt surface. Figure 13 (c) shows the calculated values of the rotational moment around the piston pin obtained by using a simple mechanical model. The vertical broken line in each figure is the crank angle at which the cylinder liner acceleration occurs.

In Figs. 13 (a) and (b), almost no difference could be seen in the maximum measured values that were output from thin-film pressure sensor 2 on the piston skirt surface due to the difference in the piston pin offset when the cylinder liner acceleration occurred, and a difference appeared only in the maximum measured values that were output from sensor 1. Consequently, it was found to be possible to evaluate the difference in the thin-film pressure on the piston skirt surface from the measured values output from sensor 1.

As a result, as shown in Fig. 13 (c), when the piston pin offset is increased, the moment around the piston pin increases, causing the top of the piston to be pushed hard against the anti-thrust side and the cylinder liner acceleration to increase.

From this fact, it was clarified that the main cause of piston slap noise is due to the rotational motion of the piston causing the contact of the top part of the piston skirt surface with the cylinder liner.

Consequently, it was possible to construct a model that considers the rotational motion of the piston in the simulation of the piston secondary motion that predicts piston slap noise, and the predictive accuracy was therefore enhanced⁽⁷⁾.

4. Conclusion

- (1) By directly installing a compact thin-film pressure sensor

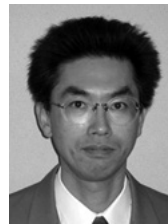
on the piston skirt surface using physical vapor deposition, it was possible to measure the oil-film pressure on the piston skirt surface when the engine was actually running.

- (2) When piston slap noise occurred, a proportional correlation was found between the cylinder liner acceleration, which is an indicator of excitation force, and the measured values obtained from the thin-film pressure sensor on the piston skirt surface, thus confirming the effectiveness of this measurement method.
- (3) The transition of the oil-film pressure on the piston skirt surface, utilizing different engine speeds and changes in the piston pin offset, was measured. The measured values of the oil-film pressure on the piston skirt surface clarified that the reason for the size of piston slap noise, which could not be explained previously from the cylinder liner acceleration alone, was the rotational motion of the piston.
- (4) Because it was possible to measure the oil-film pressure on the piston skirt surface directly under actual running conditions, the predictive accuracy of the piston secondary motion simulation was enhanced, enabling efficient countermeasures to be studied.

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