

Measurement of Piston Secondary Motion Using the New Digital Telemeter

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ABSTRACT

The authors have developed a measurement technique using a new digital telemeter which measures the piston secondary motion as ensuring high accuracy while under the operation.

We applied this new digital telemeter to several measurements and analysis on the piston secondary motion that can cause piston noises, and here are some of the results from our measurement. We have confirmed that these piston motions vary by only several tenths of millimeter changes of the piston specifications such as the piston-pin offset and the center of gravity of the piston. As in other cases, we have found that a mere change of pressure in the crankcase or the amount of lubricating oil supplied on the cylinder bore varies the piston motion that may give effect on the piston noises.

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INTRODUCTION

In response to recent environmental issues, there is a large demand for engines with improved fuel economy. Because around the piston are important parts that account for approximately half of the mechanical friction in an engine [1], efforts have been made to reduce friction by adopting short-skirt pistons and decreasing the tensile force of the piston rings. However, these cause unstable behaviors in the piston such as secondary motion and vertical piston-ring motion, which may lead to the generation of vibration noise, increased blow-by gas and lubricating oil consumption. In order to achieve both performance and reliability at a high level during the development of an engine, it is important to have an accurate grasp of physical phenomena around the piston system under running operation.

Conventionally, the measurement of the physical quantities around the piston, for example the gap, is carried out using the wired systems such as the linkage system to pick up the signals from the displacement sensors attached to the piston [2]. However, there is a possibility that the piston motion and the ring motion change because of the added inertia that hung to the piston or the connecting rod. In light

of this, the authors have developed a compact, lightweight telemeter that can accurately measure the motions of engine moving parts while under the operation [3].

This time, we applied this telemeter to measure the piston secondary motion. This paper outlines the piston secondary motion measurement system and introduces examples of measurements performed using this system.

PISTON SECONDARY MOTION MEASUREMENT SYSTEM

The piston secondary motion measurement system containing the new digital telemeter has been developed (Figure 1, Table 1) in order to realize the piston motion measurement under running operation with high accuracy.

Four eddy current gap sensors were embedded in the piston skirt in order to measure the gap between the piston and cylinder bore. In order to wirelessly transmit the sensor signal, the developed telemeter module was used on the side of the connecting rod. The wire from the sensor is routed through the piston-pin and connected to the telemeter module wiring pin. The measurement data is received by the receiving antenna mounted in the crankcase, and the receiver



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unit synchronizes the data with the crank angle data and the analog data such as in-cylinder pressure.

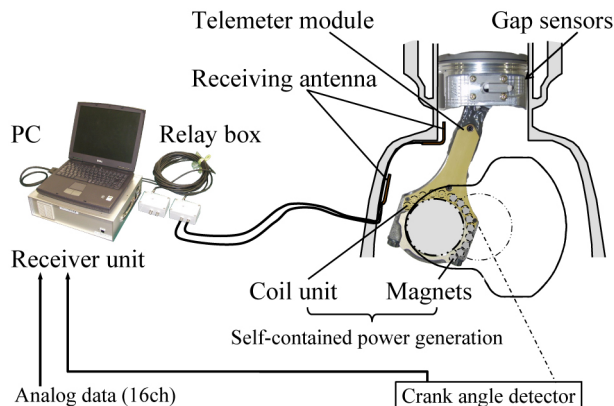


Figure 1. Measurement system

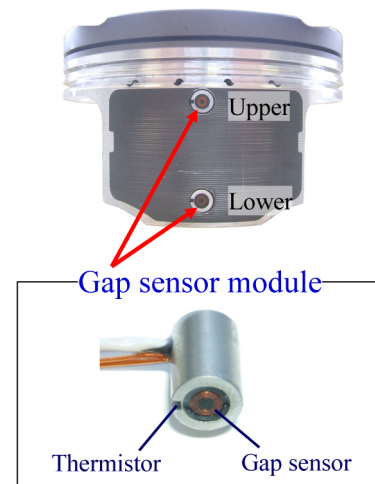


Figure 2. Sensor layout

Table 1. Specifications

Measurement object	Gap	Temperature
Sensor	Eddy current gap sensor	Thermistor, RTD
Range	0~500 μm	-30~200 $^{\circ}\text{C}$
Accuracy	$\pm 3 \mu\text{m}$	$\pm 3 ^{\circ}\text{C}$
Time resolution	24 μs	1 s
Measurement point	4 points	5 points
Transmission rate	400 μs / data , (High rate : 40 μs / data)	
Temperature range	-30~125 $^{\circ}\text{C}$, (High rate : -30~85 $^{\circ}\text{C}$)	
Acceleration	30,000 m/s^2	
Power supply	Self-contained power generation	

This measurement system was used to measure the rotational angle around the piston-pin as well as the translational displacement in the thrust direction as the piston secondary motion while under the operation.

Sensor Layout

Figure 2 shows a drawing of the piston on which the sensors are mounted. Four gap sensor modules (integrated with the compensation temperature sensor) are embedded in the piston skirt. By mounting the sensors to the thrust and anti-thrust side symmetrically, the influence of piston thermal deformation can be cancelled.

The temperature of the upper sensor module reaches up to about 140 $^{\circ}\text{C}$ under the operation, and in contrast to this, heatproof temperature of the sensor is 180 $^{\circ}\text{C}$.

Telemeter Module

The telemeter module that has been newly developed (Figure 3) is comprised of a coil unit for power generation, power control circuit, a signal processing circuit, a transmitter circuit, and a transmitting antenna. Compact and lightweight, the module is no more than 5 mm thick and weighs 20 - 30g, which allows it to be mounted on the side of the connecting rod without interfering with any moving parts in the engine. This telemeter is able to measure the gap at 4 points and the compensation temperature at 5 points (4 from the sensor and 1 from the circuit), and the measuring range, accuracy, and time resolution were at adequate levels for measuring the piston secondary motion (Table 1). Since the module can withstand temperatures from -30 to 125 $^{\circ}\text{C}$ (-30 to 85 $^{\circ}\text{C}$ for the high rate transmission type) and can also withstand an instantaneous linear acceleration of more than 30,000 m/s^2 , it is durable enough to be used in a wide engine speed range from idle to over 6000 rpm.

The signal processing unit has a proprietary “directly digitizing circuit” that we have developed (Figure 4). This is a simple circuit composed of an oscillating circuit that includes a sensor as well as a pulse generator instead of conventional components such as an amplifier and an A/D converter, and is the technology that helped to realize this compact, lightweight, and low-power-consumption telemeter module. As the circuit functions as a signal filter already, it has resistant to noise. When the inductance or resistance of the sensor varies according to the physical amounts (gap, temperature) detected by the sensor, the capacitor charging/discharging time (oscillating frequency) varies. The sensor output can be obtained as a directly digitized value by counting the pulses contained in the charging/discharging interval.

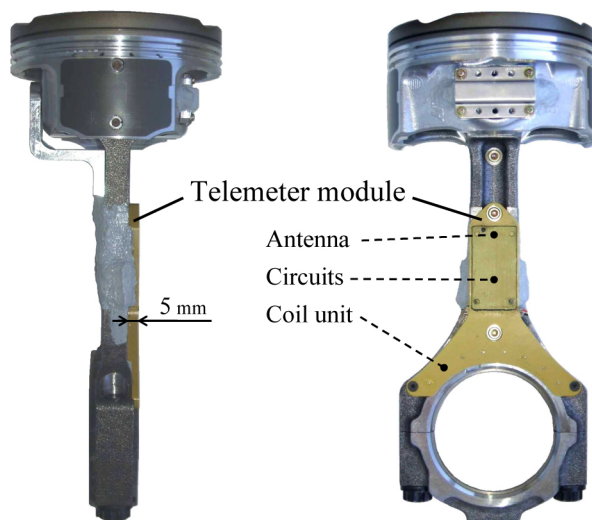


Figure 3. Telemeter module assembled to piston

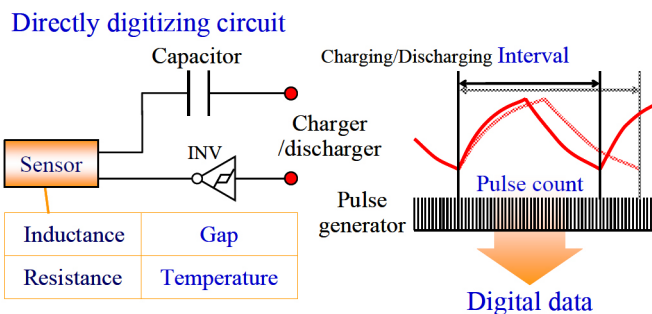


Figure 4. Signal processing method for measuring

Additionally, because the pulse generator uses less energy than the conventional amplifier, this low-power-consumption signal processing unit enables a self-contained power supply utilizing the crankshaft rotation to be adopted as a power source. While the engine is running, the coil unit for power generation in the telemeter module and magnets that are embedded in the crankshaft rotate with respect to each other, which generates power. Unlike a battery, there are no restrictions in the measurement time, and a thinner, lightweight design is possible. The engine does not have to be modified as much compared to the external inductive power for coupling, which minimizes the impact of installing the measurement system on the piston motion.

SENSOR CALIBRATION METHOD

With the telemeter module and the piston-connecting rod assembled, the telemeter outputs have been calibrated against the gap values as changing the temperatures of both the gap sensors and the telemeter module individually (Figure 5). At the same time, the internal temperatures of the gap sensor modules and the telemeter module have been also measured. When measuring in the engine, the telemeter outputs were

converted into gap values by using the calibration map that had been obtained from beforehand.

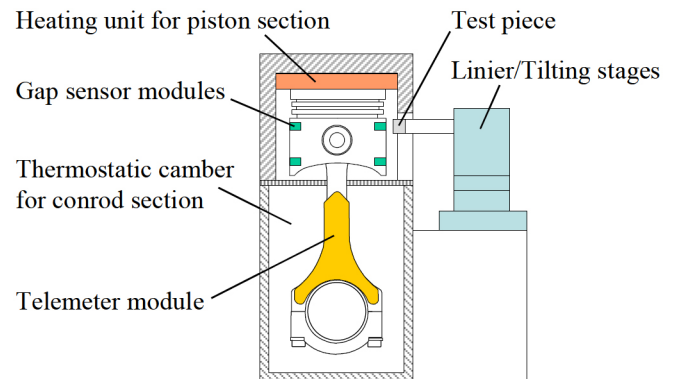
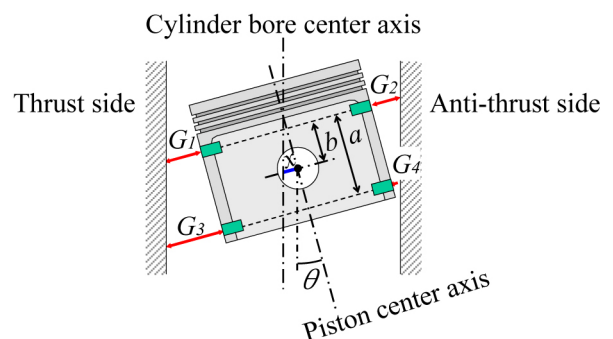


Figure 5. Method for calibrating gap sensor

PISTON SECONDARY MOTION CALCULATION METHOD

Based on the gap between the sensor in Figure 2 and cylinder bore, the piston rotational angle and the translational displacement are calculated (Figure 6).



Rotation angle : θ

$$\theta = \tan^{-1} \left[\frac{-(G_1 - G_2) + G_3 - G_4}{2a} \right] \quad \dots(1)$$

Translational displacement : x

$$x = \frac{(G_1 - G_2)(a - b) + (G_3 - G_4)b}{2a} \quad \dots(2)$$

Figure 6. Method for calculating the piston secondary motion

The rotational angle θ is the angle of inclination around the piston-pin with respect to the cylinder bore center axis, and can be calculated from Equation (1). The translational displacement x , on the other hand, is the shift length of the center of the piston in the thrust direction with respect to the center of the cylinder bore, and can be calculated using Equation (2). Here, "a" and "b" are the sensor mounting