# Verification of Contact Pressure Measurement Method for Engine Gas Sealings Using Strain Gauge

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*As engines become more powerful, the maximum pressure in the cylinder and temperature changes around the cylinder have been increasing, and the risk of a drop in the cylinder head gas sealing contact pressure during operation has risen. As such, when evaluating gas leakage, it has become necessary to consider how cylinder head gas sealings are operated. To evaluate gas sealing performance during operation, it is necessary to continuously measure the gas sealing contact pressure, including its change over time during operation. However, due to the difficulty of measurement, there is no other way to evaluate gas sealing performance other than long-term operational tests. Therefore, we developed a method to estimate sealing contact pressure from the measured strain of the tightened object near the sealing, and applied this method to a gas sealing of a cylinder head of an actual engine, and found that this method can be a useful measurement method as a result.*

## 1. Introduction

There was a case where a cylinder head gas sealing, which was newly designed for the development of a new model, caused gas leakage during its use, although it had passed bench evaluation during development. Elucidation of this phenomenon required an understanding of the change in the contact pressure during engine operation. However, there was no method to measure the contact pressure at gas sealings, which are subject to high temperature and pressure during engine operation, and it was difficult to accurately simulate the local contact pressure change and minute relative displacement at gas sealings using analysis. Therefore, there was no other way for countermeasure verification other than long-term durability tests. As such, Mitsubishi Heavy Industries Engine & Turbocharger, Ltd. has developed a method to estimate sealing contact pressure from the measured strain near the sealing, and conducted dynamic contact pressure measurement of gas sealings of a problematic engine during operation. This report describes the results of the validation of the measurement method based on elemental tests and actual equipment tests, and the results of the contact pressure measurement during operation.

## 2. Measurement method

### 2.1 Strain measuring point

**Figure 1** shows a schematic diagram of a cylinder head gas sealing to be measured. By fastening the crankcase and cylinder head with the cylinder head gasket placed therebetween using cylinder head bolts positioned around the gasket outer circumference, contact pressure is generated at the sealing to seal the high-temperature, high-pressure combustion gases inside the cylinder. One method to measure sealing contact pressure is to insert a pressure-sensitive paper into the sealing for measurement. However, this measurement method can be used only during static tightening and cannot measure dynamic contact pressure during operation because combustion gas cannot be sealed during measurement using this method with a pressure-sensitive paper. Recently, film-type and

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optical fiber-type pressure sensors have been commercially available, but their high cost and low usable temperature make it difficult to use them to measure high-temperature gas sealings. Therefore, we have developed a contact pressure measurement method using strain gauges that can be used in the temperature range of the measurement point. The following is an overview of the developed measurement method.

Sealing contact pressure causes strain in the tightened object near the sealing. This measurement method measures the strain to estimate the sealing contact pressure. The strain measurement is performed in two directions, one in the direction of the bolt axial force (using the strain gauge (i)), and the other in the horizontal direction (using the strain gauge (ii)), which is for compensating the influence of bending deformation of the measurement area described later. Since it is desirable to make the strain measurement point as close as possible to the sealing, a hole in the load direction was additionally drilled at a position in contact with the sealing, and the strain gauge (i) was attached to the sealing side of the inner surface of the hole. The diameter of the hole was set to the smallest diameter possible for attaching the strain gauge, thereby suppressing the influence of the additionally drilled hole on the sealing contact pressure. It is desirable to use strain gauges of as small a size as possible, but since the smaller the size of them, the more difficult it is to attach them; so, foil gauges with a gauge length of 1 mm, which can be attached to the inner surface of the hole, were used. Since the compressive strain decreases with depth from the sealing surface as described in the next section, the measurement position was set as close to the upper surface as possible.

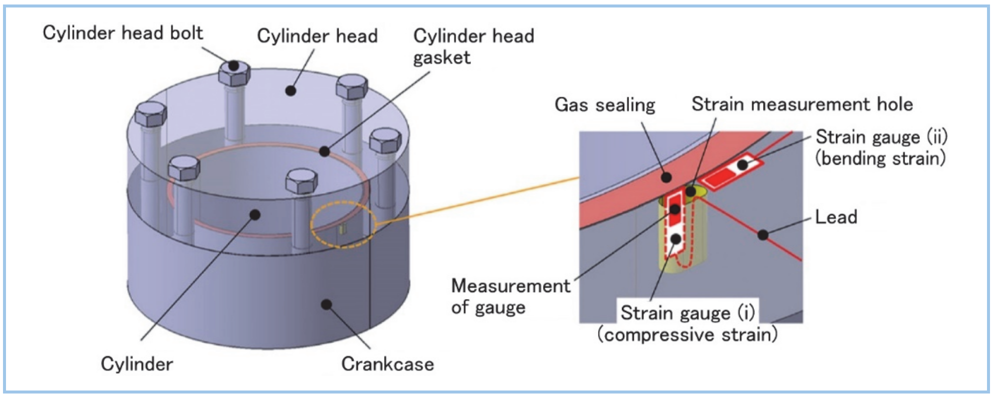


**Figure 1 Schematic diagram of cylinder head gas sealing**

## 2.2 Method of calculating contact pressure from strain measurement

(1) Conversion using strain-decreasing rate in depth direction

The compressive strain due to sealing contact pressure, which is originally in the vertical direction, is dispersed to the three axial directions as the depth increases. As a result, the compressive strain in the vertical direction decreases with depth. Therefore, the amount of strain at the sealing surface is estimated from the amount of strain at the measurement point (measured by strain gauge (i)) in consideration of the strain-decreasing rate in the depth direction. The strain-decreasing rate is defined as the ratio of the nominal contact pressure at the sealing surface to the compressive stress in the vertical direction on the inner surface of the hole, and is calculated by FEM. As an example of the calculation of the strain-decreasing rate, **Figure 2** shows the strain-decreasing rate of the cover used in "4.1 Verification of influence of bending deformation." The strain at the sealing surface is converted from the strain measurement values using the strain-decreasing rate $\eta$ (see Equation (1)). The strain-decreasing rate is determined by FEM for each measurement point since it varies depending on the shape around the measurement hole, sealing width, etc. (In this report, nominal contact pressure is defined as "total bolt axial force/sealing area".)

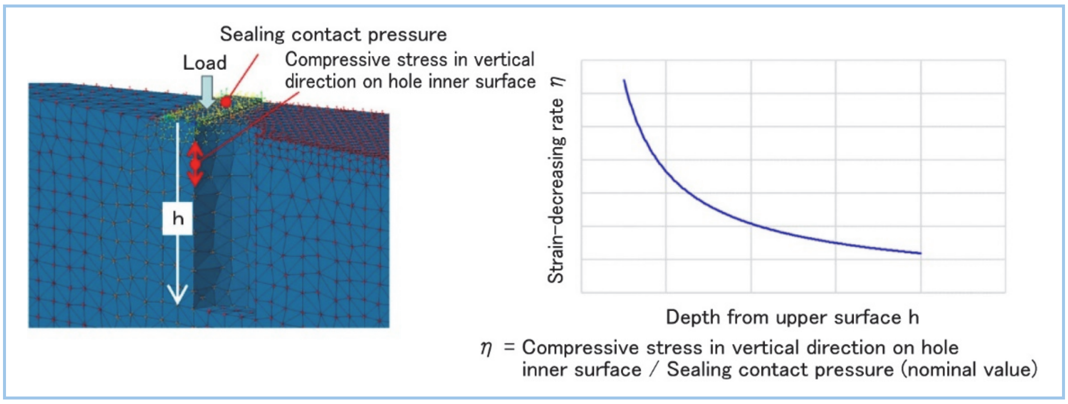


**Figure 2　Example of calculation of strain-decreasing rate**

(2)　Compensation of effect from bending deformation of strain measurement area

In a structure where bolts are placed around the sealing and the contact pressure is maintained by the bolt axial force, such as a structure in which a cylinder head gasket is installed, the contact pressure is high at points close to the bolts and low at intermediate points between the bolts, and thus the latter is often used for evaluating the sealing property. In such a structure, bending deformation occurs in the tightened object (crankcase) as shown in **Figure 3**. At intermediate points between the bolts, the tightened object is subjected to bending strain due to the bending deformation in addition to compressive strain caused by the axial force of the bolts. For this reason, the measurement of the strain gauge (i) includes not only the compressive strain, but also the strain due to bending deformation (Poisson's ratio portion of the bending strain). Therefore, the sealing contact pressure is calculated by using a value obtained by subtracting Poisson's ratio portion of the bending strain measured by the strain gauge (ii) from the compressive strain.

In this report, the sealing contact pressure ($P\_seal$) calculated by the following equations is called "strain contact pressure."

$$P\_seal = E \times \varepsilon\_seal$$
$$\varepsilon\_seal = \varepsilon\_comp' - \varepsilon\_bend \times v = \varepsilon\_comp / \eta - \varepsilon\_bend \times v \text{ ... Equation (1)}$$

$P$ : Sealing contact pressure (strain contact pressure), $E$ : Young's modulus of tightened object, $v$ : Poisson's ratio of tightened object
$\varepsilon\_seal$ : Strain used for estimation of sealing contact pressure
$\varepsilon\_comp$ : Measured compressive strain (measured by strain gauge (i))
$\varepsilon\_comp'$ : Compressive strain at sealing surface
$\varepsilon\_bend$ : Strain due to bending deformation (measured by strain gauge (ii))
$\eta$ : Strain-decreasing rate

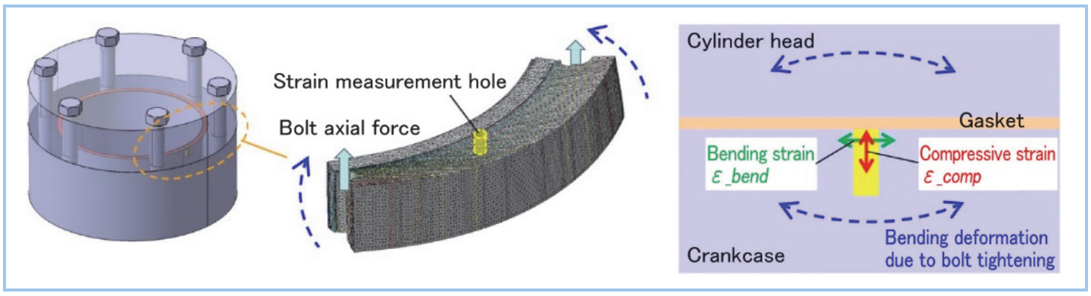


**Figure 3　Schematic diagram of bending deformation at strain measurement point**

## 3. Verification procedure

We verified this measurement method using the following procedure.

The measurement method was validated in steps (1) and (2), and its application to dynamic measurement during operation was verified in step (3).

(1) Verification using a simple tool
(2) Static verification using an actual engine
    (i) When bolts are tightened, (ii) When oil pressure simulated in-cylinder gas pressure is applied, and (iii) Measurement of temperature drift
(3) Dynamic verification during operation
    (i) During increasing in-cylinder pressure and (ii) During hot-cold cycle operation

## 4. Verification using simple tool

### 4.1 Verification of influence of bending deformation

To verify the influence of bending deformation on compressive strain, we conducted strain measurements using a cover shown in **Figure 4**. The cover was drilled to have a hole for measurement at the center between the bolts and the strain gauge (i) was attached there. The cover top surface was attached with the strain gauge (ii) based on the assumption that the top and bottom surfaces of the cover were subjected to strains that are the same but opposite in terms of positive/negative. The bending deformation caused tensile strain on the top surface of the cover and compressive strain on the bottom surface, and the strain corresponding to Poisson's ratio of the compressive strain was applied to the strain gauge (i) as tensile strain. The compressive strain measured by the strain gauge (i) was smaller because of this, but it was confirmed that by considering the bending strain measured by the strain gauge (ii), the value equivalent to the contact pressure measured by a pressure-sensitive paper can be obtained.

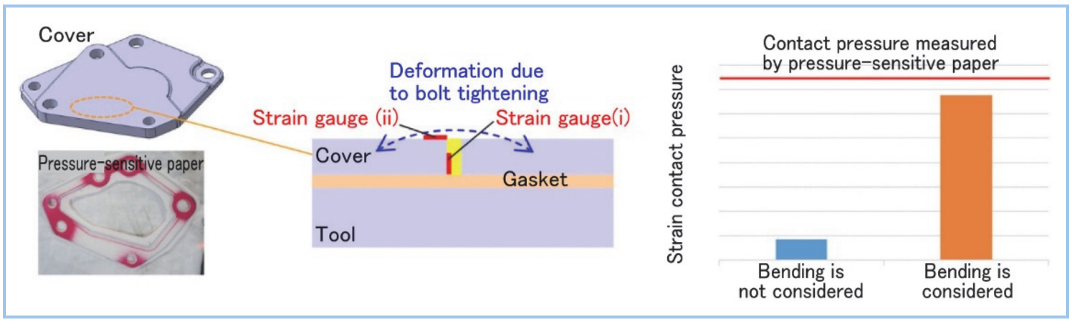


**Figure 4 Verification of influence of bending deformation**

### 4.2 Influence of gap between strain measurement point and sealing

Measuring the strain at a point close to the sealing is desirable, but a gap between the sealing and the strain measurement point may occur due to the misalignment between the gasket and the object to be tightened. To understand the influence of the gap between the sealing and the strain measurement point, we conducted verification by using a tool as shown in **Figure 5** while adjusting the gap between the sealing and the strain measurement point by changing the positioning of the gasket. The load was applied by a hydraulic press, not by bolt tightening, so that no bending deformation occurred during the measurement. When there was no gap, a value almost equal to the nominal contact pressure was obtained, but as the gap was increased, the strain contact pressure tended to decrease significantly. From this, it is important to drill the strain measurement hole in contact with the sealing and to be able to fix or adjust the gasket position to prevent it from shifting during measurement.

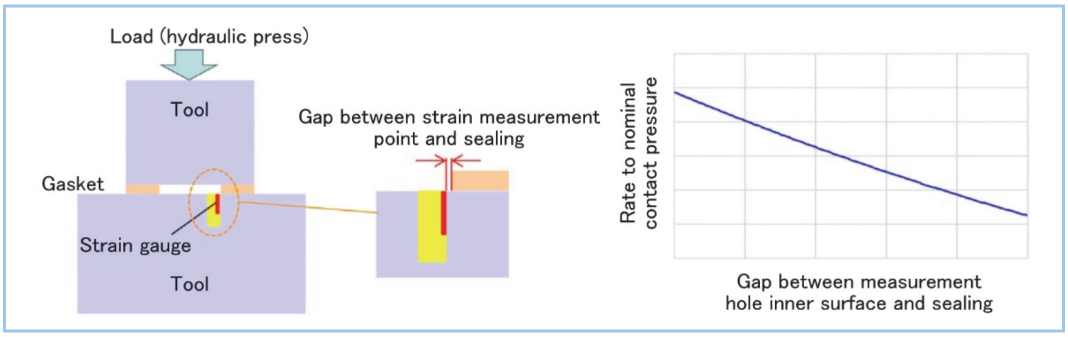


**Figure 5 Influence of gap between strain measurement point and sealing**

## 5. Static verification using actual engine

### 5.1 Measurement of static contact pressure when bolts are tightened

Next, we conducted verification using the gasket sealing of an actual cylinder head. As shown in **Figure 6**, holes for strain gauge measurement were drilled at 30° intervals on the outer circumference of the gas sealing on the top surface of the crankcase, and the strain gauges (1) and (2) were attached to compare the strain contact pressure and the contact pressure measured by a pressure-sensitive paper when the cylinder head bolts were tightened. Before attaching the strain gauge (ii), its attaching surface was channeled to avoid interference between the gasket and the strain gauge. Figure 6 compares the strain contact pressure with the contact pressure measured by a pressure-sensitive paper. In this figure, the contact pressures measured by a pressure-sensitive paper at bolt positions are measurement results obtained by using an ultra-high pressure paper (due to the measurement results beyond the measurement range of a high pressure paper), and at the other positions, a high pressure paper. The distribution of strain contact pressure in the circumferential direction generally tended to agree with that of the contact pressure measured by a pressure-sensitive paper.

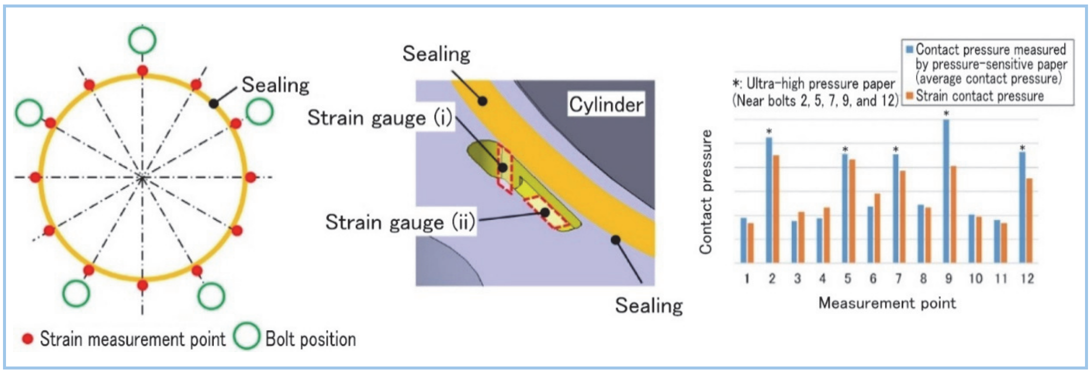


**Figure 6 Measurement of static contact pressure when bolts are tightened**

### 5.2 Measurement of static contact pressure when oil pressure simulated in-cylinder gas pressure is applied

As a preliminary verification of dynamic contact pressure measurement during engine operation, the strain measurement was conducted with the combustion chamber sealed and oil pressures equivalent to the in-cylinder pressure applied statically. The strain contact pressure tended to decrease with the increase in the oil pressure. **Figure 7** shows the amount of variation in the strain contact pressure under oil pressure load, assuming that the contact pressure when the cylinder head bolts are tightened is zero. The amount of decrease in the strain contact pressure at each oil pressure is indicated.

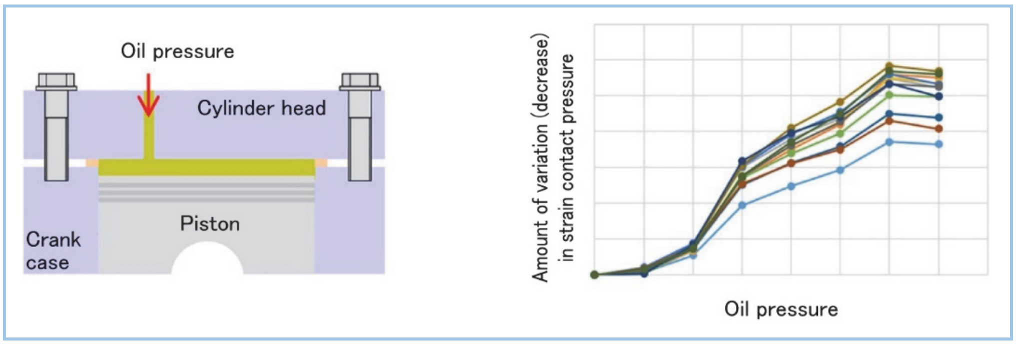


**Figure 7 Measurement of static contact pressure when simulated in-cylinder pressure is applied**

### 5.3 Measurement of strain gauge temperature drift

As a preliminary verification of the amount of temperature drift of strain measurement values due to temperature rise during engine operation, measurements were made with the areas around the strain measurement point heated by a heater. After tightening the cylinder head bolts and leaving the assembly overnight to allow the gasket to acclimate, the amount of temperature drift from room temperature to 80°C, the temperature to which the heater could heat was measured. There occurred temperature drift of the strain gauge, but it was confirmed that a stable temperature drift curve could be obtained as long as sufficient curing was performed and no delamination of the gauge occurred. However, a large drop in the contact pressure during or at the end of the measurement was observed in some measurement points. This indicates that a certain amount of hot-cold operations and leaving is required before the measured values stabilize due to factors such as drift of the strain gauge caused by insufficient curing and the degree of acclimation of the gasket.

## 6. Dynamic verification during operation

### 6.1 Contact pressure measurement during increasing in-cylinder pressure

Next, measurements with the developed measurement method were performed during actual engine operation. The measurements were made under the condition where the engine power was increased with the engine speed kept constant (i.e., the in-cylinder pressure was increased). **Figure 8** shows the in-cylinder pressure and strain contact pressure with respect to the crank angle of the cylinder where the strain measurement was performed. The strain contact pressure shown is the measurement at one representative point out of 12 measurement points. It was observed that the strain contact pressure decreased when the in-cylinder pressure increased due to combustion, and that the amount of variation (decrease) in the strain contact pressure increased as the maximum in-cylinder pressure increased. This figure also compares the amounts of variation in the strain contact pressure during operation and under oil pressure load as shown in Figure 7. The two show generally the same trend, which confirms that the developed measurement method can measure the dynamic contact pressure during operation.

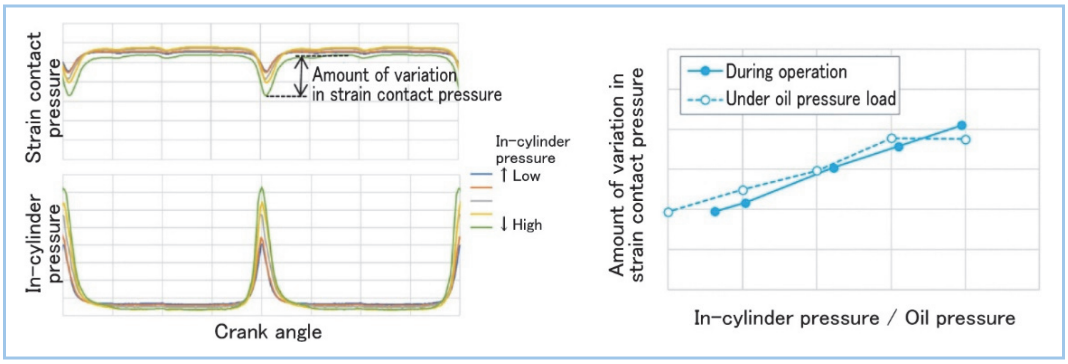


**Figure 8 Contact pressure measurement during increasing in-cylinder pressure**

### 6.2 Contact pressure measurement during hot-cold cycle operation

Measurements with the developed measurement method were performed during actual engine operation in a hot-cold cycle pattern with abrupt temperature changes, which cause severe conditions for gas sealings. Before starting the measurement, a hot-cold cycle operation was repeated as curing, and the temperature correction of the gauge measurement was performed by measuring the temperature near the gauge and using the temperature drift curve obtained in Section 5.3 It is considered that the strain measurement was made possible even during temperature changes by conducting the above procedure. **Figure 9** shows the operation pattern, the amount of variation in the strain contact pressure, and the temperature of the strain measurement point. It was found that certain adjacent measurement points exhibited significantly different behavior regarding the strain contact pressure. There were large differences in the transient contact pressure gradient and temperature between those two measurement points, so careful verification of sealing properties is required.

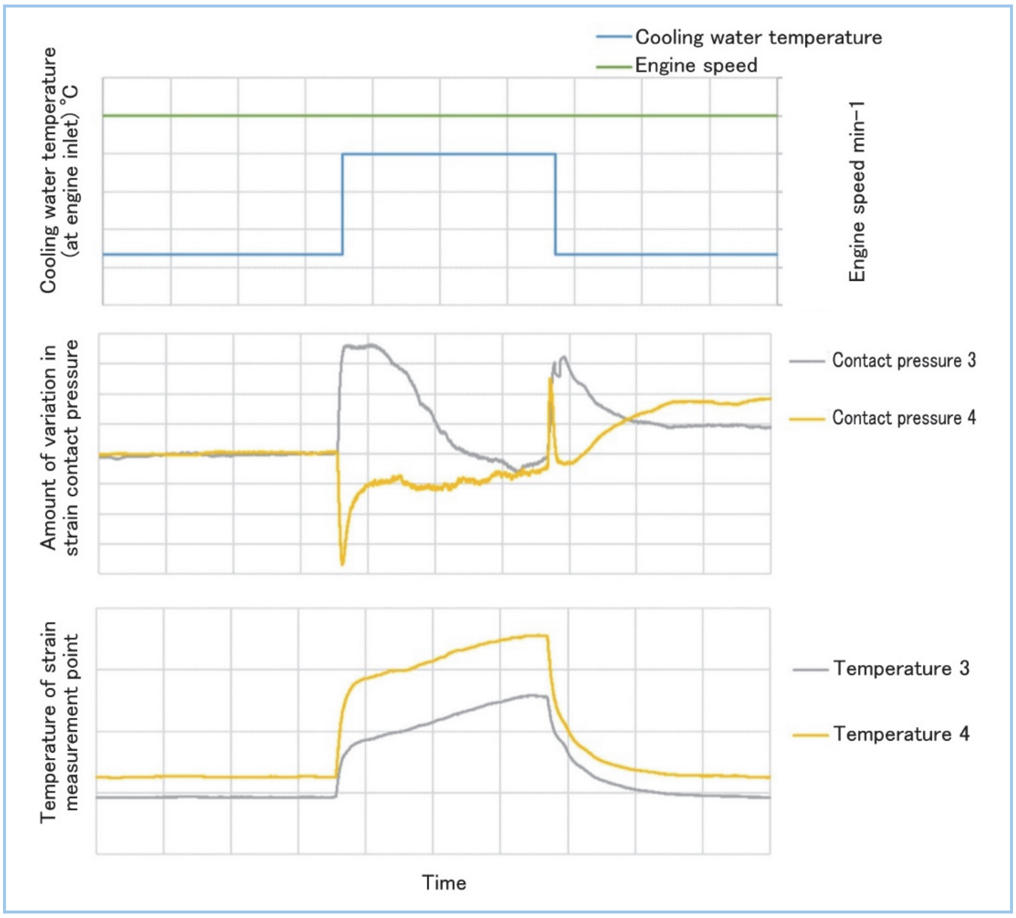


**Figure 9 Contact pressure measurement during hot-cold cycle operation**

## 7. Conclusion

- To achieve dynamic contact pressure measurement during engine operation, we developed a contact pressure measurement method using strain gauges and validated the measurement method. It was confirmed that the measurement method could measure the dynamic contact pressure in actual equipment tests, indicating that this method can be a useful measurement method.
- It was discovered by this method that the contact pressure gradient increases transiently in certain areas during hot-cold cycle operation. This method identified areas with concerns about sealing that do not become apparent during constant-load, steady-state operation.
- In the verification process, measurement failures and variations in the amount of temperature drift due to delamination of strain gauges and insufficient curing were observed. Additionally, other issues such as the strain gauge attaching position and the accuracy of the gasket position are also acknowledged. We will continue to improve our measurement methods.