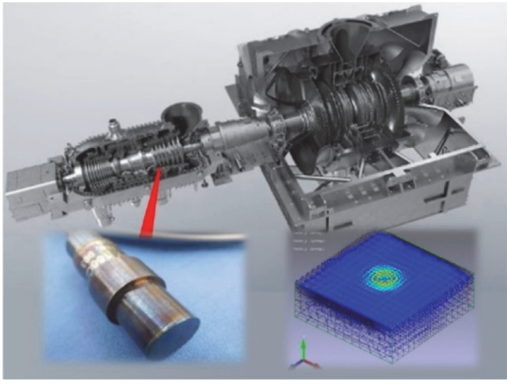
# Development of Eddy Current Gap Sensor for Accurately Measuring Small Clearance in High-Temperature Environments up to 600°C



**TAKEHIKO YAMAGUCHI**[*1] **MAKOTO KONDO**[*2]
**RYO KAWABATA**[*3] **KOHEI OZAKI**[*4]
**KOTA TANAKA**[*5] **TATSURO FURUSHO**[*6]

*While the decarbonization of power sources is progressing, thermal power generation facilities, which are positioned as an important source of power supply also in the future because of their flexibility in output adjustment, must be made more efficient to reduce $CO_2$ emissions. In a steam turbine, which is a key component of a thermal power generation facility, appropriate management of the small clearance between the rotating and stationary parts in the steam turbine casing enables efficient conversion of steam flow into rotational energy, leading to the improvement in power generation efficiency. Therefore, we developed an eddy current gap sensor to manage the small clearance in the casing of a steam turbine during operation, and confirmed that the sensor can measure small clearances of 0 to 3.5 mm within ±120 μm of measurement accuracy for more than 1,000 hours.*

## 1. Introduction

Toward the realization of carbon neutrality, it is expected that the ratio of power generation without using fossil fuels, such as renewable energy and nuclear power, will continue to increase. However, in the process of the spread of renewable energies, thermal power generation, which is capable of flexible output adjustment, is positioned as an important electricity supply source (1). To steadily promote both stable power supply and decarbonization of power systems, increasing the efficiency of thermal power generation to reduce $CO_2$ emissions is essential. Mitsubishi Heavy Industries, Ltd. (hereinafter referred to as MHI) has been applying the latest high-efficiency technologies to steam turbines (hereinafter referred to as ST), which are the main power generation equipment, and fuel consumption reduction from enhanced efficiency has helped realize the added value of $CO_2$ emission reduction (2).

STs have a sealing mechanism between the rotating blades or rotor and the stationary casing to prevent leakage of the working fluid, that is, steam. By keeping the small clearance in this sealing mechanism narrow, the amount of steam leakage can be reduced and the steam flow can be efficiently converted into rotational energy of the turbine blades. However, if the clearance is excessively narrow, contact can occur during ST operation, resulting in damage. As such, there was a need for a technology that could monitor the clearance during ST operation. Therefore, MHI developed an eddy-current gap sensor that enables long-term monitoring during operation, even in the ST casing, where the temperature and pressure can rise up to 600°C/10 MPa.

This report presents an overview of measures to improve the measurement accuracy and durability of the gap sensor to realize stable clearance measurement in ST casings for more than 1,000 hours, which is equivalent to a commissioning period. In addition, this report explains the results obtained by applying the developed sensors to the combined cycle power plant

---

[*1] Chief Staff Manager, Electron Physics Research Department, Research & Innovation Center
[*2] Research Manager, Strength Research Department, Research & Innovation Center
[*3] Strength Research Department, Research & Innovation Center
[*4] Machinery Research Department, Research & Innovation Center
[*5] Engineering Manager, Steam Turbine Engineering Department, GTCC Business Division, Energy Systems
[*6] Steam Turbine Engineering Department, GTCC Business Division, Energy Systems

demonstration facility in our Takasago Plants (hereinafter referred to as T-Point 2) and plants already delivered to overseas customers.

## 2. Outline of gap sensor

**Figure 1** shows the appearance of the gap sensor. The gap sensor's main body is made by RDP of the United Kingdom. A coil is arranged inside the metal casing of the gap sensor. The signal obtained by the gap sensor is transmitted to the measurement amplifier via a stainless steel-coated mineral insulated (hereinafter referred to as MI) cable inside the ST casing, where the temperature and pressure can be high, and via a polyurethane-coated soft cable outside the ST casing.

**Figure 2** visualizes the spatial distribution of eddy currents generated on the measurement target by the gap sensor through electromagnetic field analysis. When the gap sensor is placed near the measurement target and an AC voltage is applied to the coil, an eddy current is generated on the surface of the target due to electromagnetic induction. The strength of the eddy current depends on the distance between the gap sensor and the measurement target, i.e., the clearance; the eddy current becomes stronger when the clearance is small, and weaker when the clearance is large. The generated eddy current forms a magnetic field and changes the impedance of the coil placed inside the gap sensor. This change can be used to measure the clearance.

The signal obtained by the gap sensor and transmitted to the measurement amplifier is output as a voltage amplitude. The impedance of the coil, which is the output of the gap sensor, varies depending on the distance between the gap sensor and the measurement target as described above, and also on the effect of ambient temperature. The ambient temperature of the gap sensor applied to STs varies from room temperature to about 600°C. Therefore, it is necessary to create a calibration curve that takes into account the effect of ambient temperature through testing. We created a calibration curve by installing the gap sensor in an electric furnace and measuring the output voltage of the measurement amplifier while changing the distance between the gap sensor and a calibration test piece made of the same material as the measurement target and the temperature in the furnace.

**Figure 3** shows a typical example of a calibration curve obtained while changing the clearance from 0 mm to 3.5 mm and the ambient temperature from room temperature (20°C) to 600°C. The clearance when applying the gap sensor to an ST is determined by placing a thermocouple near the gap sensor, observing two parameters, the output voltage of the gap sensor and the ambient temperature measurement results, and applying them to the calibration curve.

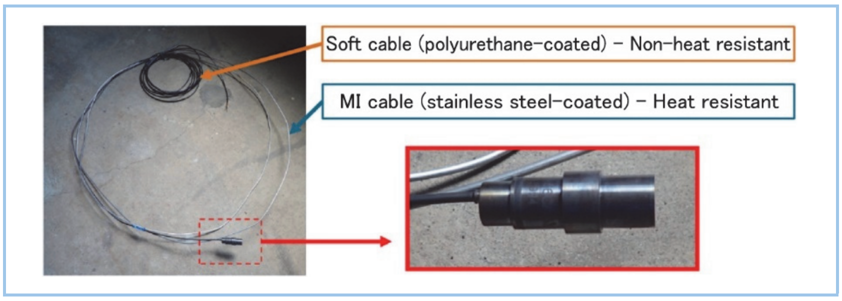


**Figure 1 Appearance of gap sensor**

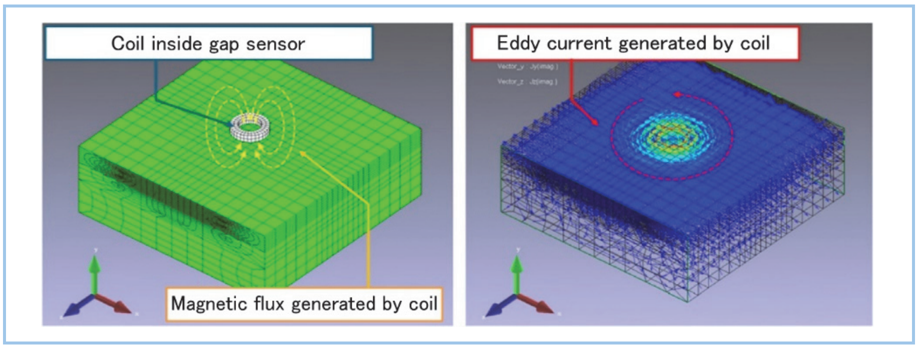


**Figure 2 Visualization of eddy currents generated on measurement target by gap sensor through analysis**

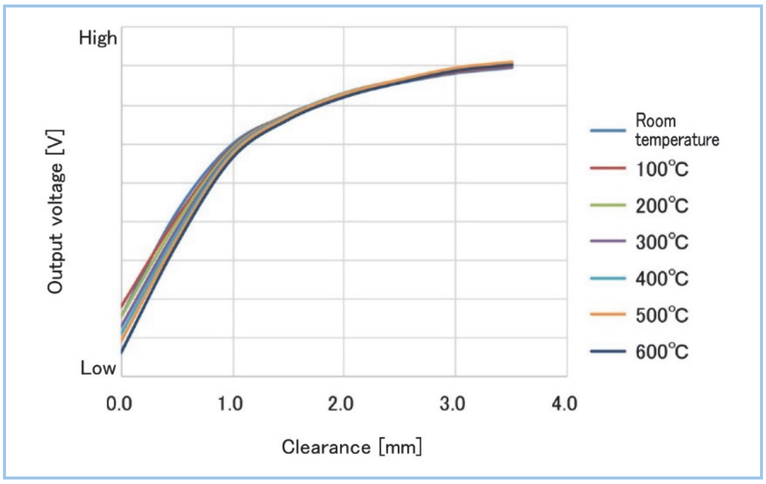


**Figure 3 Typical example of gap sensor calibration curve**

## 3. Measures to improve measurement accuracy and durability of gap sensor

### 3.1 Improvement of measurement accuracy

To evaluate the sealing performance of STs, the gap sensor is required to have high measurement accuracy. Therefore, we verified the measurement error caused by error factors assumed when using the gap sensor. **Figure 4** shows the result obtained from testing. The result shows that when all error factors are accumulated, a large measurement error occurs, indicating insufficient accuracy in the evaluation of sealing performance. In particular, the measurement margin of error caused by the measurement equipment and the MI cable is large, accounting for about 80% of the total measurement margin of errors. Therefore, we took measures to reduce the measurement errors of these two error factors with a large measurement margin of error to improve the measurement accuracy.

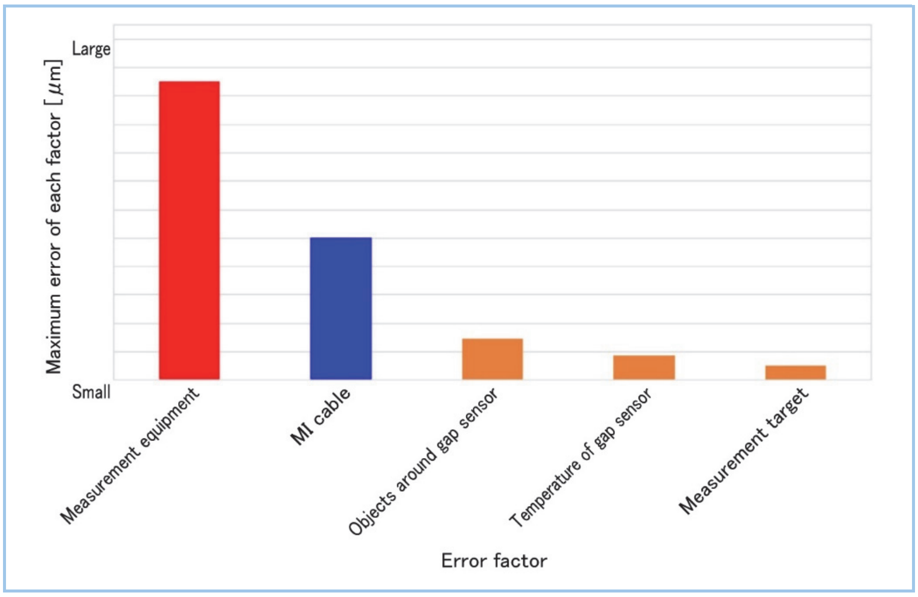


**Figure 4 Error factors of gap sensor and error caused by each factor (before measures taken against error factors)**

The gap sensor measurement equipment is placed on the same floor as the ST casing due to the cable length that transmits the gap sensor signals. The temperature in the vicinity of the ST casing changes by up to about 20°C between the shutdown and operation states, and it was found that these temperature changes in the vicinity of the ST casing affect the measurement equipment, resulting in a large measurement margin of error. Therefore, to prevent the ambient temperature of the measurement equipment from changing, we installed it in a thermostatic chamber. As a result, the measurement error caused by changes in the ambient temperature of the measurement equipment was reduced to about 1/10.

It was also found that the measurement error caused by the MI cable transmitting gap sensor signals was also large. The verification results showed that it was effective to set the carrier frequency lower than that of the manufacturer's original amplifier to reduce the MI cable-induced measurement error. Therefore, we applied a lock-in amplifier instead of the manufacturer's original measurement amplifier, thereby reducing the measurement error caused by the MI cable to about one-third.

**Figure 5** shows the results of these measures taken against the error factors. As shown in this figure, the accumulated measurement error was reduced by approximately 70%, and the maximum measurement error of the gap sensor was improved to ±120 μm.

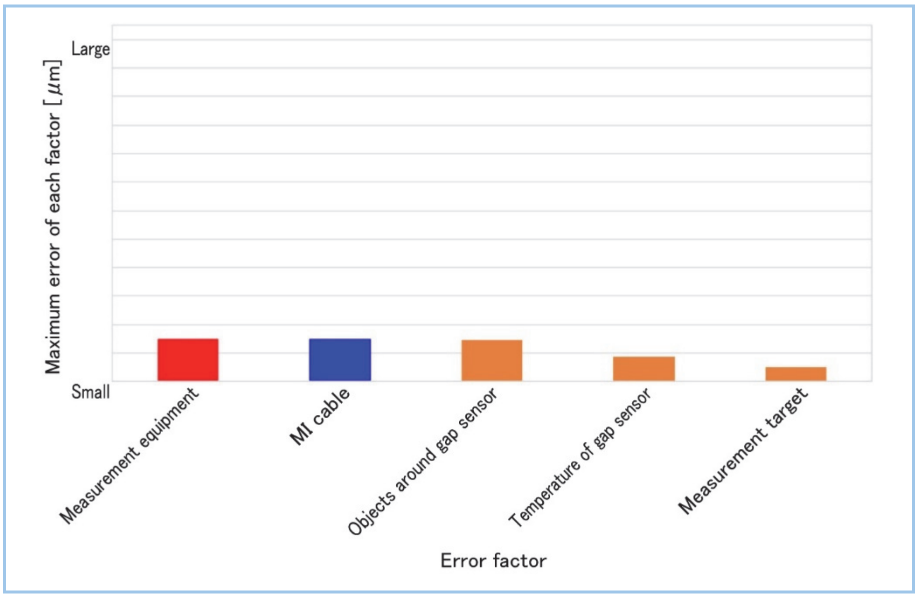


**Figure 5 Error factors of gap sensor and error caused by each factor (after measures taken against error factors)**

## 3.2 Improvement of durability

Gap sensors are required to be durable enough to be able to keep monitoring clearance during commissioning for about 1,000 hours. However, when gap sensors were applied to STs prior to the development reported in this paper, approximately 70% of them were disconnected or short-circuited within a short period of time after the start of the ST operation and became unable to be measured. Therefore, we worked on improving the durability of gap sensors.

According to the record before the development in this report, the MI cable was installed so as to have a very small bending radius of about R5 to R10 in the wiring in the ST casing, and it was presumed that the cable was subjected to excessive bending load, resulting in disconnection and signal interruption. Therefore, we established a wiring procedure to control the MI cable to have a large bending radius as shown in **Figure 6**. Consequently, the breakage of the MI cable was eliminated.

**Figure 6 Improvement of MI cable wiring procedure**

In addition, it was found through the verification that disconnections and short-circuits also occurred in signal lines and coils in the metal casing of the gap sensor. We discussed these problems with the sensor manufacturer and made minor improvements to the structure inside the metal casing. As a result, these problems were virtually eliminated.

As a result of these measures, 39 of the 41 sensors used at T-Point 2 (more than 95%) were able to perform measurement for more than 1,000 hours, meaning that the durability of the sensors was greatly improved.

## 4. Application to clearance control technology

Whether the ST is operating or in a stopped state, if the clearance can be controlled externally, narrower-than-before clearance can be used, thereby improving the performance and operability of the ST. To achieve this, a technology (3) to actively control the clearance by heating the outside of the ST casing to cause thermal elongation of the ST casing has been developed, and the gap sensors are used to monitor the clearance control status. **Figure 7** shows the installation position of the gap sensors for monitoring the clearance control technology (4). In this case, the gap sensors are installed at the outer gland section outside the ST casing so as to sandwich the rotor.

Using the clearances measured by the installed gap sensors, the internal clearances can be predicted. By controlling the heater heating amount and lifting the ST outside casing during ST startup based on the predicted clearances, it is possible to prevent contact between the turbine blade tip and the ST casing when the rotation speed rises, and to maintain the clearance at an appropriate value during rated operation.

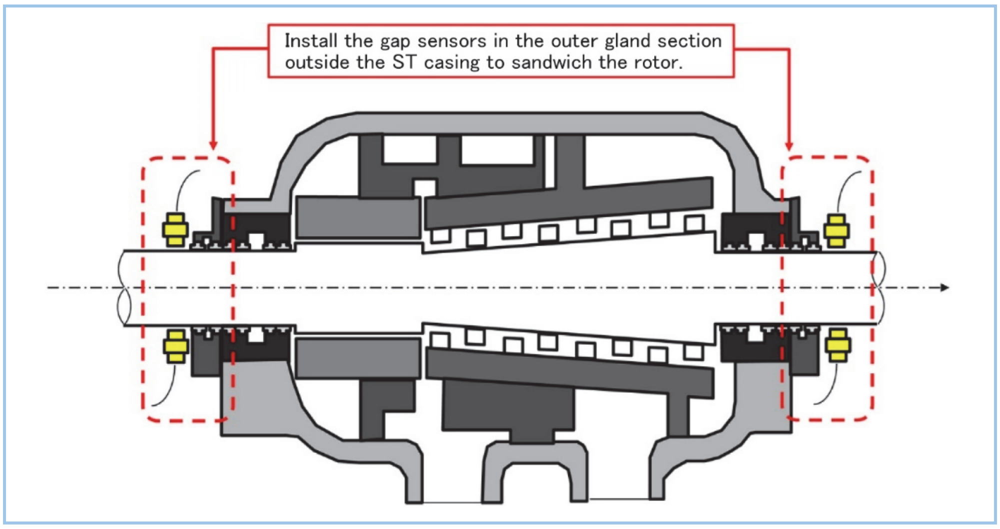


**Figure 7 Gap sensor installation position for monitoring clearance control technology**

## 5. Application to T-Point 2 and plants delivered to customers

A total of 85 of the developed gap sensors have been applied to T-Point 2 and two overseas plants so far, and are establishing track records. In these plants delivered to the customer, the gap sensor was applied at the trial operation stage just before delivery. **Figure 8** shows, as a representative example, the application of the gap sensors to T-Point 2 and the results of clearance changes during operation measured by them installed in the intermediate pressure ST casing so as to sandwich the rotor. The clearance measurement results of the upper- and lower-installed sensors show that when the upper clearance increases, the lower clearance decreases by approximately the same amount, and conversely, when the upper clearance decreases, the lower clearance increases by approximately the same amount. This means that the results of the upper- and lower-installed sensors agree, indicating that the change in clearance was measured correctly over a period of 2,500 hours. By combining the clearance measurement results obtained by the sensors with the clearance control technology described in Chapter 4, we were able to improve the power generation efficiency by approximately 0.1%.

In addition, Active Clearance Control (hereinafter referred to as ACC) seals, which mechanically change their clearance in response to pressure changes in the ST casing, are applied to T-Point

2, and the gap sensors are also used to check whether the amount of movement of the ACC seals is as planned. In this way, the gap sensor can also be used to evaluate the validity of the operation of mechanical parts in the ST casing, which was difficult to ascertain in the past.

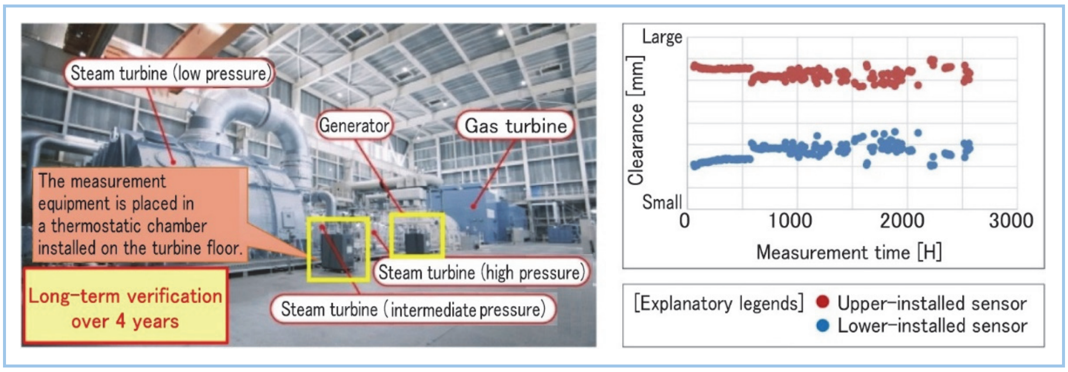


**Figure 8 Application of gap sensors to T-Point 2 and obtained data**

## 6. Conclusion

We have developed an eddy-current gap sensor that can accurately grasp clearances in steam turbines, which are the key components of thermal power generation facilities, during their operation, and confirmed that the sensor can measure clearances of 0 to 3.5 mm within ±120 μm of measurement accuracy for more than 1,000 hours. The sensor has been applied to T-Point 2 and the plants that have already been delivered to overseas customers. By combining the sensor with the clearance control technology, we have been successfully improving the power generation efficiency compared to the past. MHI will continue to develop technologies to achieve both highly efficient power generation and reduced environmental impact.

## References

(1) Agency for Natural Resources and Energy, “Future Thermal Power Policy” (in Japanese) https://www.meti.go.jp/shingikai/enecho/denryoku_gas/denryoku_gas/pdf/074_10_00.pdf
(2) T. Nakano et al, “Initiative for $CO_2$ Emission Reduction by Steam Turbine Retrofitting with High-efficiency Technologies” Mitsubishi Heavy Industries Technical Review Vol.60 No.3 (2023)
(3) T. Nakano et al, “Development of Latest High Efficiency Side Exhaust Steam Turbine” Mitsubishi Heavy Industries Technical Review Vol.58 No.3 (2021)
(4) M. Kondo et al, “Monitoring device, computer-readable storage medium for storing monitoring program and monitoring method for rotary machine, and rotary machine equipment” JP7403684B2, 2023.12.14