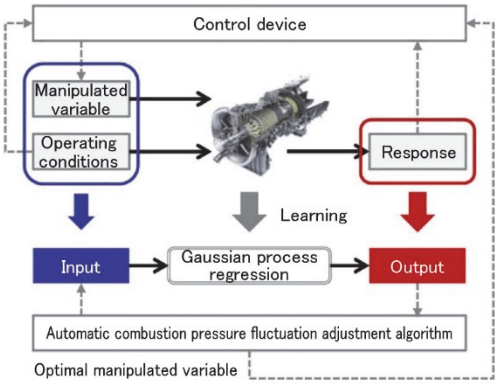
Achieving Stable Combustion Operation of Gas Turbines: AI-Based Automatic Adjustment of Combustion Pressure Fluctuation



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Power generation gas turbines carry the risk of significant equipment damage caused by combustion pressure fluctuations under high-temperature combustion for high-efficiency operation. The technology in this report allows the AI to learn combustion pressure fluctuation characteristics in real time and makes oscillation predictions that account for the AI's prediction confidence, thereby automatically adjusting operating conditions cautiously in low-prediction-confidence regions and proactively in high-prediction-confidence regions. By utilizing this technology, combustion pressure fluctuations have been successfully and rapidly suppressed while reducing the risk of incorrect adjustments. This report describes an overview of this technology and the results of verification at Mitsubishi Heavy Industries, Ltd.'s demonstration power generation facility.

1. Introduction

Power generation gas turbines are required to operate under high-temperature combustion conditions to achieve higher efficiency and increased power output. On the other hand, under these high-temperature combustion conditions, self-excited oscillations occur due to the coupling between unsteady heat release fluctuations of the flame and the acoustic field of the combustor. If these combustion pressure fluctuation levels become excessive, there is a risk of causing damage to combustor and turbine components. Therefore, it is necessary to suppress combustion pressure fluctuation levels below pre-established allowable limits.

To address this issue, Mitsubishi Heavy Industries, Ltd. (hereinafter referred to as MHI) has developed, commercialized, and applied an automatic combustion pressure fluctuation adjustment system [(1)] using machine learning technology to actual units. However, as gas turbines move toward even higher efficiency and flexible operation, sudden changes in combustion pressure fluctuation characteristics have occurred, necessitating combustion pressure fluctuation adjustment in a shorter period of time. Therefore, a new automatic combustion pressure fluctuation adjustment technology has been developed using Gaussian Process Regression as a machine learning method to predict combustion pressure fluctuations [(2)].

Subsequently, Chapter 2 provides an overview of the automatic combustion pressure fluctuation adjustment technology; Chapter 3 presents the verification results at a demonstration power generation facility; and Chapter 4 provides a conclusion.

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2. Automatic combustion pressure fluctuation adjustment technology

A power generation gas turbine consists of three elements: a compressor, a combustor, and a turbine, as shown in **Figure 1**. The compressor compresses air to a high pressure; the combustor injects fuel into this air and combusts it, generating high-temperature and high-pressure gas; and the turbine is rotated by this gas to obtain power for power generation. Gas turbine combined cycle (GTCC) power generation, which drives a steam turbine using high-temperature exhaust gas exceeding 600°C from the gas turbine, enables high-efficiency operation with a power generation efficiency of 64% or higher.

Power generation gas turbines apply automatic control to achieve high availability, reliability, and high-efficiency operation throughout their life cycle spanning several decades; they also require automatic reduction of combustion pressure fluctuation levels. Typically, fuel is supplied to the combustor from multiple fuel systems. For example, the combustor in **Figure 2** is equipped with a main system, a pilot system, and other systems. Regarding combustion pressure fluctuations, appropriate control of operating parameters, such as the distribution of fuel to each fuel system, can change the combustion state and reduce oscillations. However, combustion pressure fluctuations possess nonlinear response characteristics relative to the supplied air conditions, fuel composition, and load conditions. Furthermore, individual differences exist between each gas turbine, making it difficult to accurately understand the characteristics in advance, which complicates the design of an appropriate control system. To address these situations, the automatic combustion pressure fluctuation adjustment technology automatically adjusts operating parameters to suppress the occurrence of combustion pressure fluctuations and enables operation in a consistently stable combustion state.

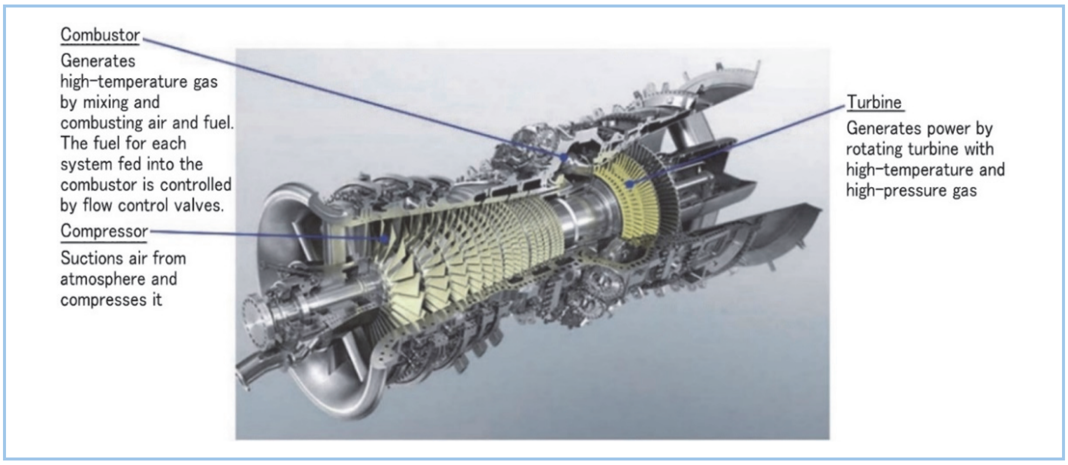

Figure 1 Configuration of gas turbine

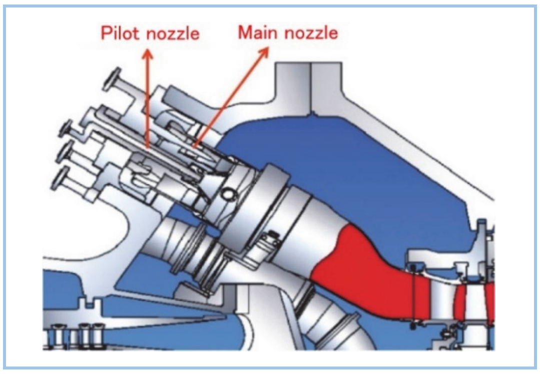

Figure 2 Schematic diagram of combustor

2.1 Conventional automatic combustion pressure fluctuation adjustment technology

MHI commercialized an automatic combustion pressure fluctuation adjustment system applying machine learning technology in 2004 and has installed it in commercial plants to reduce combustion pressure fluctuations. **Figure 3** shows the configuration of this system. Based on data collected during operation, this system uses machine learning to perform online modeling of the relationship between combustion pressure fluctuations and process values that affect them, such as air flow rate and fuel distribution. When combustion pressure fluctuations occur, the system calculates an operating region that reduces the oscillations based on the estimation model and automatically adjusts the fuel distribution to operate within that region.

Initially, a relatively simple nonlinear regression model was adopted as the combustion pressure fluctuation prediction model for this system. This nonlinear regression model predicts combustion pressure fluctuation levels based on process values such as air flow rate and fuel distribution. The model is based on the premise that characteristics near the operating point are locally approximated to a nonlinear model, and adjustments are limited to that vicinity.

On the other hand, with the response to higher efficiency and flexible operation driven by increasing needs for gas turbines in recent years, sudden changes in combustion pressure fluctuation characteristics have occurred, necessitating combustion pressure fluctuation adjustment in a shorter period of time. However, in the case of adjustments based on the aforementioned nonlinear regression model, the combustion pressure fluctuation characteristics can only be predicted within a local approximation range; therefore, the adjustment amount per iteration is small, and it takes time to reach the optimal adjustment. Furthermore, if proactive adjustments are made to reduce combustion pressure fluctuations, the system enters regions without operating experience, posing a risk of conversely increasing oscillations.

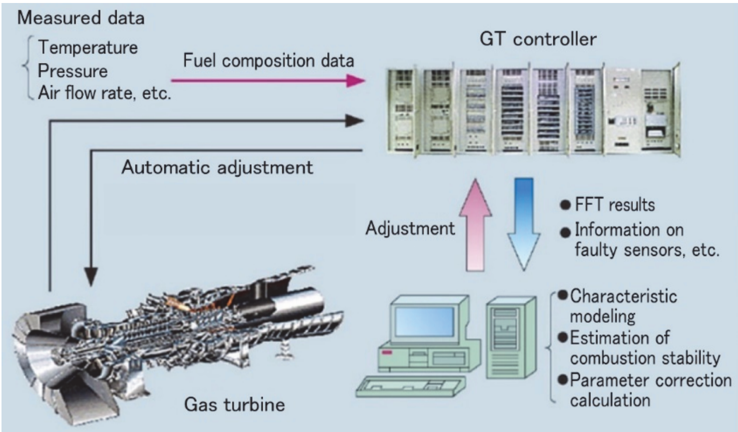

Figure 3 Configuration of automatic combustion pressure fluctuation adjustment system

2.2 New automatic combustion pressure fluctuation adjustment technology applying Gaussian process regression

To resolve this issue, a regression method called Gaussian process regression [3], as shown in **Figure 4**, is used as a machine learning model to represent combustion pressure fluctuation characteristics. Gaussian process regression is a method capable of calculating the uncertainty of estimated values and is characterized by increased uncertainty in unlearned regions. **Figure 5** shows the framework of the automatic combustion pressure fluctuation adjustment technology applying Gaussian process regression. The automatic combustion pressure fluctuation adjustment algorithm assumes a worst-case scenario where combustion pressure fluctuations reach the maximum level considering the estimation uncertainty, and derives the manipulated variables within a range where this worst-case value satisfies the allowable operating limits to achieve proactive adjustment to reduce combustion pressure fluctuations while preventing adjustments into regions without operating experience, which carry the risk of increased oscillations.

Figure 6 shows the state of the automatic combustion pressure fluctuation adjustment. The dashed lines in Figure 6 indicate two possible combustion pressure fluctuation patterns (Case 1 and Case 2), and both (a) and (b) correspond to conditions where sufficient operating data for learning has been collected. It can be seen that in known operating regions where learning data exists, Gaussian process regression well represents each combustion pressure fluctuation characteristic (dashed lines in Figure 6) with small estimation uncertainty, enabling automatic adjustment to the appropriate fuel distribution in a short time when combustion pressure fluctuations occur. On the other hand, in (c), due to a lack of learning data, it is unknown what combustion pressure fluctuation characteristics will emerge in the unknown operating region, and an increase in estimation uncertainty is observed. Accordingly, the adjustment amount is restricted, considering the possibility that the combustion pressure fluctuation level may rise in the unlearned region (corresponding to Case 1). In the example of (c), it is difficult to foresee whether the combustion pressure fluctuation characteristics of Case 1 or Case 2 will emerge, and therefore, this adjustment judgment is considered appropriate.

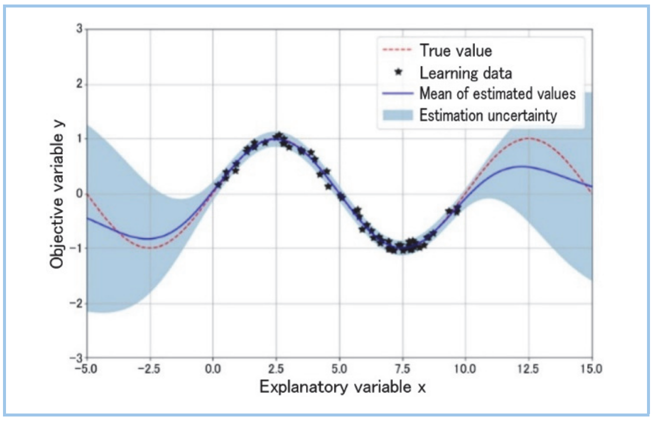

Figure 4 Estimation by Gaussian process regression

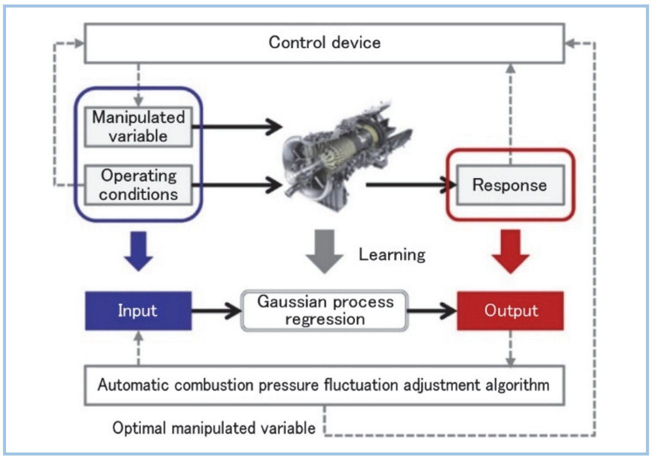

Figure 5 Framework of automatic combustion pressure fluctuation adjustment technology applying Gaussian process regression

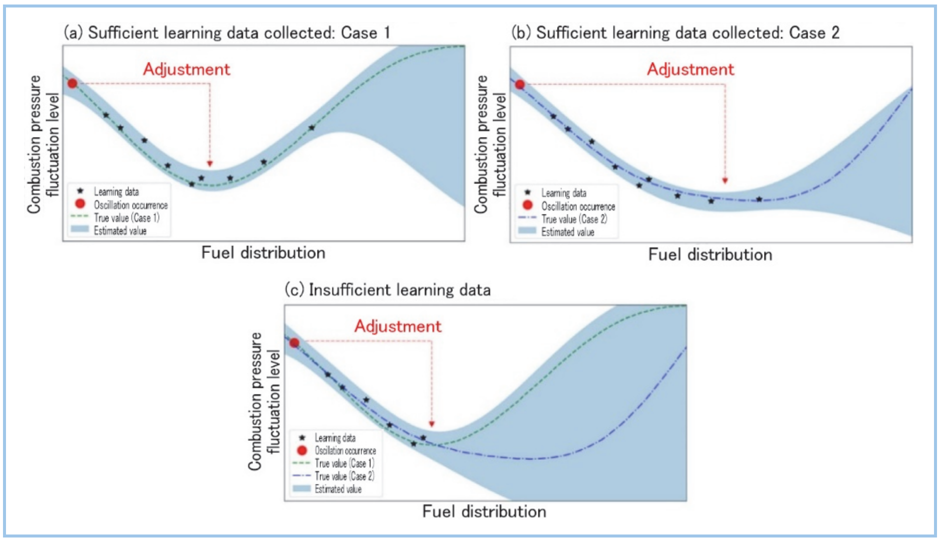

Figure 6 State of automatic combustion pressure fluctuation adjustment using Gaussian process regression

2.3 Automatic exploration technology for operating data applying Gaussian process regression

By reducing regions without operating experience in the method described in Section 2.2, the regions where proactive adjustment is possible will increase. Therefore, as shown in **Figure 7**, a method is considered to automatically transition the operating state toward regions where the estimation uncertainty by Gaussian process regression is large, to explore and collect data from those regions. In this exploration, surrounding operating points are explored by automatically increasing or decreasing the fuel distribution in small increments so that combustion pressure fluctuations remain stable within allowable limits. By collecting characteristic data regarding the combustion state at these operating points, more operating data is accumulated, aiming for improved reliability.

During the automatic exploration, potential exploration points are evaluated using Gaussian process regression before the actual exploration. If there is a risk that combustion pressure fluctuations may exceed the allowable limits, the points in question are excluded from the exploration targets, ensuring that operating data is explored and collected safely.

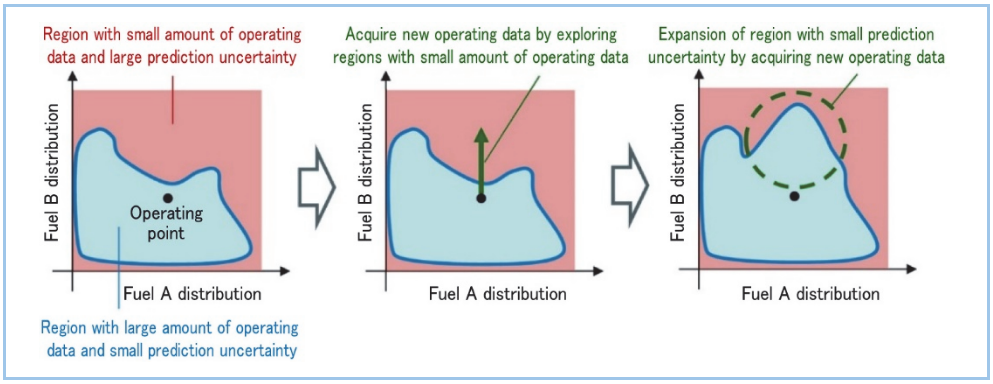

Figure 7 Schematic of automatic exploration using Gaussian process regression

3. Verification results at demonstration power generation facility

Verification of this system using an actual unit was conducted at the T-Point 2 Combined Cycle Power Plant (**Figure 8**), a demonstration facility located in Takasago City, Hyogo Prefecture. By manually adjusting the fuel distribution, combustion pressure fluctuations were intentionally generated to verify whether the technology could reduce these oscillations. As a result of the verification, it was confirmed that, as shown in **Figure 9**, the fuel distribution was appropriately adjusted upon the occurrence of combustion pressure fluctuations, and the oscillations were rapidly reduced without causing any damage to the equipment.

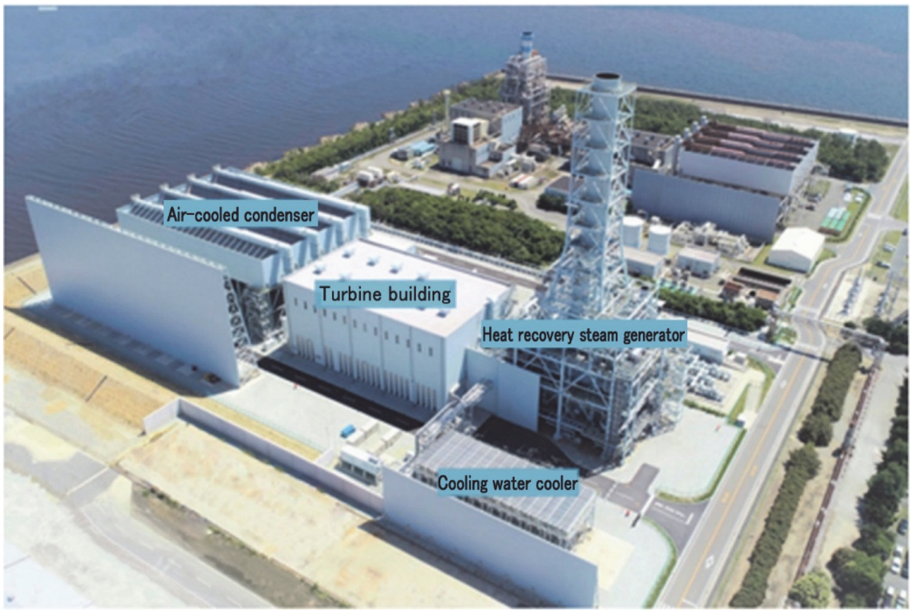

Figure 8 Demonstration power generation facility

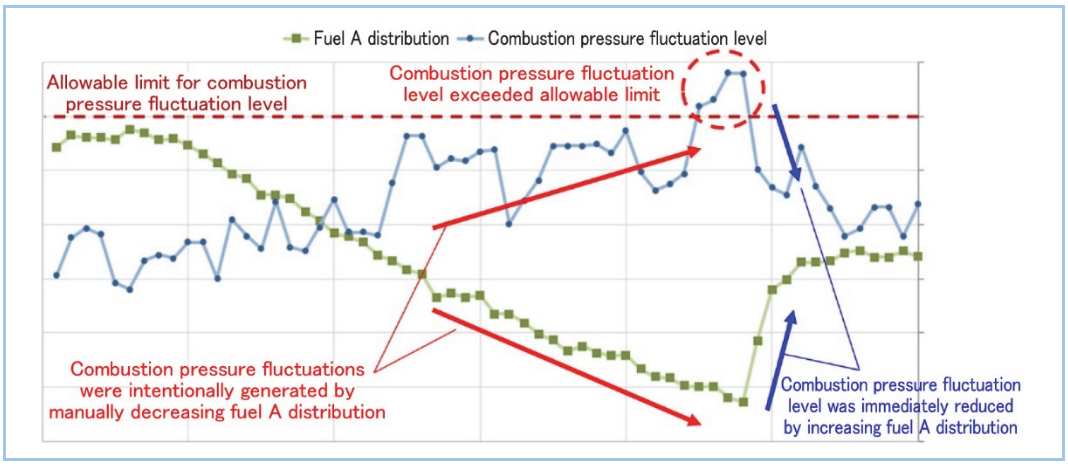

Figure 9 Verification results at demonstration power generation facility

4. Conclusion

This report has introduced an overview of the automatic combustion pressure fluctuation adjustment technology that allows the AI to learn combustion pressure fluctuation characteristics in real time and makes oscillation predictions that include the AI's prediction confidence, thereby achieving rapid suppression of combustion pressure fluctuations while reducing the risk of incorrect adjustments, and the results of its verification at MHI's demonstration power generation facility.

The technology was commercialized in fiscal 2022 and has completed its long-term verification at T-Point 2 and commercial plants; it is currently being sequentially deployed to other commercial plants. MHI will continue to promote the development of this technology to ensure its compatibility with new gas turbine models scheduled for future development.

References

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