（様式２）

学位論文の概要及び要旨

氏　　名　池田 和史

題　　目　Prediction and Suppression Method of Combustion Oscillation in Premixed Gas Turbine Combustor（ガスタービン予混合燃焼器の燃焼振動予測手法と対策手法）

学位論文の概要及び要旨

This thesis regards the development of gas turbine combustors for power generation. A gas turbine consists of a compressor, a turbine and combustors, which is a device to exchange the energy of high temperature compressed gas to the mechanical energy. With attention on environmental protection and economic efficiency, recent power generation gas turbines require to be achieved high efficiency and low emissions. To achieve this, higher temperatures and lean combustion tend to be developed for gas turbine combustors. In such combustion conditions, excessive pressure fluctuation may occur inside the combustor. This pressure fluctuation is usually not so intense, but in some combustion conditions, this may increase at a certain frequency due to a self-excitation mechanism, and may reach a noticeable level. This self-excited excessive pressure fluctuation, which is called combustion oscillation, may impair the operation of the gas turbine engine and may result in hardware damage. Therefore, combustion oscillation has been one of the main problems for gas turbine development.

There have already been many studies on combustion oscillation. The basic theory says that combustion oscillation occurs when the self-excitation rate due to the interaction between heat release fluctuation and pressure fluctuation becomes larger than the acoustic damping rate of the system. According to this basic theory, with regards to suppression methods for combustion oscillation, two general concepts can be proposed. One of them is the decrease of the self-excitation rate by detuning of the interaction of heat release fluctuation and pressure fluctuation. Another one is to append the acoustic damping. In particular, to achieve the former method, analysis of the interaction of heat release fluctuation and pressure fluctuation is needed, and there have been many studies on this mechanism already. Further, to capture the essential part of mechanism, linear analysis has been often discussed. The discussions on this mechanism can be divided into two, namely, the acoustic system driven by heat release fluctuation, and heat release fluctuation driven by the acoustic system. In the conventional method, the acoustic system driven by heat release fluctuation has been formulated from the linearized basic equations of fluid dynamics. The linear wave equation having a source term of heat release fluctuation and also an inhomogeneous term of temperature gradient has been derived. In this formulation, there remains a question of the reason why other inhomogeneous terms can be neglected. Also, in the conventional method, the $N-\tau$ model has been discussed as the mechanism of heat release fluctuation driven by the acoustic system. The $N-\tau$ model which is represented as $q'/\bar{q} = N\left[1-\exp(-i\omega\tau)\right]v'/\bar{v}$, is a transfer function between the heat release fluctuation and acoustic fluctuation, where q, v, i, ω, τ, and N are the heat release density, velocity, imaginary unit, angular frequency, advection time until the flame from the fuel nozzle of fuel mass fraction fluctuation, and the sensitivity of combustion to acoustic fluctuation related to the reaction index of the reaction model as of $q \propto Y^N$ where Y is fuel mass fraction, respectively. The symbols $\bar{\bullet}$, $\bullet'$, and $\hat{\bullet}$ are the mean flow component, the perturbation component, and variables in the Fourier domain, respectively. According to prior studies, the instability of the combustion-acoustic system is influenced strongly from this phase of the transfer function. The coefficient N has been considered as a real number, and hence, many recent studies have focused on the estimation of the delay time τ as a cause of the phase of the transfer function. According to their results, τ is related to the advection time until the flame from the fuel nozzle of fuel mass fraction fluctuation. If these were correct, combustion oscillation could be suppressed easily by mixing the fuel well. However, unfortunately, combustion oscillation may occur even in a combustor burning well-mixed fuel, such as a low emission combustor, and this suggests that $N-\tau$ model should have a delay time factor other than the fuel advection time.

The objective of this thesis is the suppression of combustion oscillation. To achieve this objective, two kinds of methodology were developed. One is the decrease of the self-excitation rate by detuning of the interaction of heat release fluctuation and acoustics. The other is to append the acoustic damping. This thesis is not trying to reduce the fluctuation that has already become large enough, rather, trying to develop the method to suppress the growth up of small fluctuation such that the linear approximation holds.

To achieve the detuning of the interaction of heat release fluctuation and acoustics, this thesis develops the analysis method of combustion-acoustic linear instability which solves the problem of conventional method mentioned above. First, the nonlinear wave equation equivalent to the basic equations of fluid dynamics is formulated, and the physical meaning of the inhomogeneous term included in the conventional equation is discussed. As a result, it is found that this inhomogeneous term is a kind of heat release fluctuation mechanism due to fluctuation of how to receive the heat of the fluid. Later in this thesis, fuel mass balance in the combustion region is discussed using the basic theory of combustion, and through this discussion, the coefficient N of the $N-\tau$ model is corrected to a complex number by taking account of the reaction time. This thesis shows the accuracy of the corrected models of this thesis as verified by simple burner tests. The corrected models can be expected to be applicable even to combustion oscillation occurring in a combustor burning well-mixed fuel, such as a low emission combustor. Details of the analysis models and verifications are discussed in sections 2 and 3 of the thesis.

This thesis develops the three-dimensional finite element analysis for analyzing the models with the three-dimensional geometry of combustor and the three-dimensional physical properties of combustion. Generally, eigenvalues of the combustion-acoustic system are evaluated as complex numbers. The real and imaginary parts of these correspond to the resonance frequencies and the damping characteristics, respectively. So, complex-eigenvalue analysis can be considered as an instability analysis method. However, the matrix scale in actual practice is usually very large, and therefore, the accuracy and cost of large scale complex-eigenvalue analysis had been a problem. As a solution of this problem, this thesis proposes an approximate calculation method, in which the complex-eigenvalue problem is expanded by the orthogonal real-eigenvectors. Verification results show enough approximate accuracy and drastic improvements in calculation efficiency. Details of the finite element analysis method and complex- eigenvalue analysis method are discussed in section 4.

As can be seen from the analysis, combustion oscillation is sensitive to slight differences of combustion conditions. If it is possible to append enough acoustic damping over broad combustion conditions, suppression effect could be expected without having to worry about slight differences of combustion conditions. This thesis proposes that a perforated structure called an "acoustic liner" is applied to the combustor wall, and shows the analysis accuracy when compared to the laboratory test results. Furthermore, verification using an actual engine test, the acoustic liner has found that can suppress combustion oscillation in an actual gas turbine combustor effectively. Details of the suppression method are discussed in section 5.

As the results of research and development, the recent gas turbine engine has succeeded that suppress combustion oscillation and enable the stable operation. These results can be expected to be a basis of the successor gas turbine combustor.