# Active Combustion Control and 3D-LIF Measurement for Unstable Premixed Swirl Flame

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### 1. Introduction

Studies of oscillatory combustion have been carried out by many researchers. In past investigations, general considerations of oscillatory phenomena were investigated mainly. However, in these days, active combustion control (ACC) of the oscillatory flame has a lot of attention as a technical method of clean combustion to reduce its pollutions. Several studies succeeded at the application of active combustion control meant to suppress longitudinal mode oscillations in laboratory scale combustors [e.g., 1-3]. In these cases, systems have used various means of actuation like loudspeakers, fuel-flow modulation, and so on. In recent concerns about the ACC, development of the control system to achieve real time observation is a key point of ACC investigation. Furthermore, the important point is to consider delay times caused by the period of input and output signals with a control theory. Under these circumstances, Zinn and coworkers [e.g., 4-6] were investigated the ACC strenuously for gas turbine combustor. Contents of their researches are the experiment, numerical simulation, and furthermore theoretical analysis. Candel and coworkers are also one of the ACC research group, and they carried out an experimental study based on adaptive control algorithms [7]. Ghoniem and coworkers investigated the ACC with theoretical and numerical analyses [8]. In their papers, it is proposed that developing the models for the acoustics, the heat-release dynamics, their coupling, and fluid dynamics is physically based.

In this study, the subjects are to develop the closed-loop active control for combustion instability based on a control algorithm and to obtain the information about reacting zone in a flame using the LIF measurement (PLIF and 3D-LIF). The active control algorithm was developed with H2 controller based on modal analysis. The modal analysis is useful to determine the system identification with an experiment. The information from LIF measurement is used to understand the oscillatory mechanism, and furthermore, it will be important data to develop a laser-used ACC system in a future.

#### 2. Experimental setup and Control Method

Figure 1 shows schematics of premixed combustor and swirl-type flame holder. Size of combustor is  $150 \times 150 \times 300$  (mm), and the diameter of swirl-type nozzle is 30 mm. The nozzle has twelve vanes and its angle  $\theta$  is 45 degrees. Pure CH<sub>4</sub> gas was used as a fuel and it was premixed with air before the ignition.

As a control system, microphone and loudspeaker were equipped for a sensor and actuator. To control



Fig. 1 Schematics of combustor and swirl-type flame holder

the gain of loudspeaker, MATLAB/Simlink and dSPACE units were installed in the ACC system. The active control algorithm was based on the H2 control method using modal analysis. This is for the feedback control system and its purpose is to reduce the order of developed controller. To develop a controller with minimum order, active real time observation will be possible.

## 3. Results and discussions

To understand the combustion phenomenon of swirled flame, it is important to examine how and when the oscillatory combustion occurs. Figure 2 shows the status of flame, that means a map of combustion condition. Oscillatory combustion occurs when methane flow rate is ranging from 1.5 l/min to 2.0 l/min in fuel-rich conditions in our case. When the methane flow rate is ranging from 1.75 l/min to 2.50 l/min, another type of fluctuated flame is observed. These fuel flow rates correspond to the fuel-lean conditions. Since the oscillatory mode is different each other, oscillatory flames characterized by fuel-rich conditions are defined as Type-A and the flames belonged to the fuel-lean region are as Type-B, respectively: Type-A



Fig. 2 Map of combustion characteristic

flame is held at the outer rim of the nozzle and Type-B flame is stabilized at the inside rim. Since the flame is fluctuated with being hold or without being hold at the nozzle rim, it seems that the source of combustion noise may exist in fluid dynamics.

As a detail analysis of noise source, frequency analysis is performed using FFT analyzer. In this case, microphone is set above the combustor. Results are indicated in Fig. 3 to confirm that the main frequency is about 385 Hz in fuel-lean region. In the case of fuel-rich condition, the frequency is about 100 Hz. If the flame temperature is estimated with 1000 K approximately, the Helmholts frequency is calculated as 406 Hz. Hence it seems that the higher frequency is based on the Helmholts type oscillation.



Fig. 3 Oscillatory frequency at various equivalence ratio conditions

To visualize the oscillatory phenomena, LIF measurement is carried out. 3D-LIF is an application of graphical analysis and four laser sheets are formed with a double pulse YAG laser and two dye laser systems. From the result of 3D image, it is possible to examine spatial conditions. Figure 4 shows the 3D-results of OH radical distribution. This result is the case of Type-B flame. In the all images, unburnt region is observed near the swirl holder. Reaction of OH radical is the strongest at the position of (d). It is thought that the strong reaction is due to the interaction of fluid from the rear vane. These results imply that heat release rate is irregular at each location.



Fig. 4 OH radical images taken by 3D-LIF measurement system

Fundamental characteristic of the oscillatory frequency is clarified with the frequency analysis. Next step is to develop the ACC system based on a control algorithm. As the approach to develop the controller, there are two ways of problem to solve. One is a forward problem based on physical model. The other is an inverse problem without physical model. In this study, the frequency response of acoustic field is measured experimentally and the characteristic of frequency mode is identified. Then, equation of state is described for the acoustic field and the ACC system based on a feedback dynamic controller is designed. In the case, the performance of noise reduction is appreciated with H2 norm of closed-loop transfer function. The following performance function is used to develop the ACC system.

$$J = \int_0^\infty \left( x^T Q x + u^T R u \right) dt \tag{1}$$

Here, the first term in right hand side means oscillation energy and the second one is control energy. Q and R are the weighting matrix.

Figure 5 indicates a schematic of the developed ACC model. In this figure, G(s) is a transfer function of the system and K(s) means that of controller.  $Z_{21}$  and  $Z_{22}$  mean the valuation amount of input signal to the loudspeaker and that of noise level, respectively. Figure 6 shows a time history of acoustic pressure. After the control is on, it is found that noise level is reduced to half level of the initial energy. In this study, a closed-loop feedback controller based on inverse problem is proposed to apply the ACC system. Since the controller is developed with experimental modal analysis base, it is considered that high performance of noise reduction is elicited. In the future work, development of the controller based on physical model and establishment of real time observation system for adequate sensor are searched.



Fig. 5 schematic of the developed ACC model



Fig. 6 Performance of noise reduction

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