Combustion Instability Analysis of a Model Gas Turbine by Application of Dynamic Mode Decomposition

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ABSTRACT

Dynamic mode decomposition (DMD) technique is applied to analyze combustion instabilities in a model gas turbine combustor. The flame transfer function (FTF) obtained by the DMD method agrees with the experimental results qualitatively. However, FTF results show that the perturbation frequency with the largest gain is 100Hz, which contradicts the 1000Hz with the largest amplitude in the fast Fourier transform (FFT) results. In order to figure out this, gains and damping coefficients of all resonance frequencies are calculated by DMD technique. Results show the possibility that the model combustor has high-frequency instabilities as a result of coupling between flame and chamber responses. Another finding is that to obtain a pure FTF, the combustor must be removed to exclude coupling of chamber response with flame response.

Key Words: Gas turbine, Combustion instability, Dynamic mode decomposition, Transfer function

1. Introduction

Recently, gas turbines have been developed in various aspects to improve performance and reduce pollutants (e.g., NOx). The lean premixed pre-vaporized combustion is a widely used method. However, the fuel-lean burning results in a long ignition delay time which causes combustion instability more probably[1].

The phenomenon of combustion instability produces noise and vibration. If vibration level is kept small, it can be ignored or allowed. However, if the pressure fluctuation reaches a value much greater than the mean pressure, the combustor may be over-heated and flames may flow backward and damage the injection system. Moreover, the combustor will be damaged, or serious problem such as an engine explosion may take place. Therefore, combustion instability evaluation for low equivalence ratio condition or a combustor with specific geometric shapes must be performed[2-4].

In order to predict the combustion instability, and to secure the accuracy, various analysis methods have been proposed by introducing hydrodynamics, acoustics and control theory[5,6]. One of the most widely used methods is the transfer function which can identify coupling between the heat release of flame and the velocity or pressure perturbation. Two frequently mentioned transfer functions are the flame transfer function (FTF) representing the flame response and the acoustic transfer function (ATF) representing the chamber response. This method has been studied for a long time[7,8]. In addition, another popular method is the fast Fourier transform (FFT). The FFT is a
method to process pressure signals detected at monitor points for a period of time on the frequency basis. However, there is a limit to analyze the entire combustor domain or determine the acoustic mode associated with the measured frequency by using FFT. Therefore, dynamic mode decomposition (DMD) is proposed to overcome these limitations. The DMD technique was developed recently in the field of mode decomposition. It can extract the linear variation from the instantaneous fields data obtained for a fixed time interval[9-11].

In this study, combustion instability was evaluated using DMD technique. The flame transfer function was evaluated by DMD in our previous research[12]. And, it is compared with the experimental FTF in the present paper. The problem mentioned in the previous work is that the FTF results show a maximum gain at 100 Hz, while the FFT results show a maximum amplitude at 1000 Hz[12]. The present study is focused on this problem and the phenomenon is analyzed in detail by using DMD technique.

2. Methodology

2.1. Experimental setup

The model gas turbine combustor was 1/3 scaled down from the GE7EA gas turbine. The facility consists of a swirl injector, a quartz combustor and a steel combustor with a movable plug nozzle. More information can be checked in the previous study and will not be described in detail here[12-14]. The schematic diagram of a model chamber is shown in Fig. 1.

In order to investigate the effect of fuel composition on the combustion characteristics in the combustor, five cases were selected in the previous study[12]. The most unstable case among them is selected in the present study, and its boundary conditions are listed in Table 1. Fuel is a mixture of 37.5% hydrogen and 62.5% methane and oxidizer is air.

2.2. Flame transfer function

The FTF ($G_f$) is a kind of transfer function that represents the relationship between the input variable (velocity or pressure fluctuation) and the output variables (heat release rate fluctuation). Here, FTF measurements are used by means of the classical $n$-$\tau$ model[3, 6]:

\[
FTF(\omega) = G_f = \frac{\dot{Q}' / \dot{Q}_{mean}}{u' / u_{mean}} = n(\omega)e^{i\omega\tau} \tag{1}
\]

and gain and phase of FTF is defined as:

\[
Gain = n(\omega) = |G_f| \tag{2}
\]

\[
Phase = \omega \tau = \tan^{-1}\left(\frac{G_{f,im}}{G_{f,real}}\right) \tag{3}
\]

where $\omega$ is the angular frequency and $\tau$ is time delay. $\dot{Q}'$ is the heat release rate fluctuation measured by photomultiplier tube (PMT) with OH$^*$ filters. Velocity fluctuations $u'$ is measured by hot wire anemometer (HWA). The flame
transfer function can be obtained with the experimental data.

2.3. Dynamic mode decomposition

The DMD technique is a method of extracting linear fluctuations in the instantaneous fields of a data set for a fixed time interval. Based on the OH\(^*\) radical image measured in experiments, the FTF can also be calculated by DMD technique. And, the calculated FTF will be compared with experimental results in later sections.

One advantage of DMD technique is to show the fluctuation field of target variables (velocity, pressure, and heat release rate, etc.) on the 2D plane. This would be useful if we want to observe the distribution of variable fluctuations in the combustor. Another advantage is that resonant frequencies and their corresponding damping coefficients can be calculated. A negative damping coefficient means that the amplitude of its corresponding resonant frequency will decay and the oscillation will be stabilized. Conversely, if the damping coefficient is positive, the amplitude will increase and it will be unstable. This is a useful tool in analyzing the combustion instability. More details on DMD technique can be found in our previous studies\[9-12\].

3. Results and Analysis

In the selected unstable case, the DMD technique was used to calculate its flame transfer function in the previous study\[12\]. The obtained flame transfer function is compared with experimental results as shown in Fig. 2. It can be seen that although the calculated FTF is slightly different from the experimental one, they are qualitatively consistent with each other: gains of the FTF peaks at 100 Hz, and then repeatedly increase and decrease from 200 Hz to 1000 Hz. The phase decreases linearly with the perturbation frequency. This shows that the time delay is independent of frequency and maintains a fixed value, which is consistent with the phase lag definition \(\omega \tau\) in Eq. (3).

Fig. 3 is the FFT result obtained from the experimental pressure signal without perturbation. It can be clearly seen that the maximum amplitude appears at 1029 Hz. This is inconsistent with the FTF result mentioned above, which shows the maximum gain value at 100 Hz.

In order to analyze this discrepancy, gains are obtained for all resonance frequencies with perturbation frequencies, \(f_p\) of 100 Hz and 1000 Hz. Results are shown in Fig. 4. To calculate the gain of FTF, the heat release rate fluctuation and velocity fluctuation need to be calculated firstly according to Eq. (1). Velocity fluctuation is easy to get because it was already determined when the perturbation was applied. The calculation of heat release rate fluctuation requires DMD technique and the detailed process can be found in our previous study\[12\]. Unlike the FTF shown in Fig. 2, the target frequency here is not just the perturbation frequency, but all the resonant frequencies. That is, heat release rate fluctuations at all of the resonant frequencies caused by the velocity perturbations of 100 Hz and 1000 Hz are calculated, respectively. And then, the ratio of the heat release rate fluctuation and the velocity fluctuation is calculated. Finally, the absolute value is taken, which is the
value of gain. When the perturbation frequency is 100 Hz, it can be seen from Fig. 4(a) that the value of the gain at 100 Hz is small. Instead, larger gain values show up at 1000 Hz and the other higher frequencies. In a similar way, with the perturbation frequency of 1,000 Hz, gain at 1,000 Hz is relatively small. It means that after perturbation is applied, gains of other resonance frequencies may be higher than the gain at the perturbation frequency. One possible reason for this is that the flame response is coupled with chamber response. It will be considered in a future work.

One advantage of the DMD technique is that it can not only obtain the gain of a specified position but also visualize the planar results of the heat release rate fluctuation at the specified resonant frequency, which facilitates comparative study and analysis. With the 100 Hz perturbation case taken as an example shown in Fig. 5, the planar results of heat release rate fluctuations at the six resonant frequencies are seen. In the result of 136.8 Hz close to 100 Hz, the value of heat release rate fluctuation is not so high. However, results of the smaller frequency 49.36 Hz and larger frequency 1079.7 Hz show broad areas with high fluctuation. This is the same as the conclusion from Fig. 4.

Regarding perturbation frequencies, the FTF results show that 100 Hz will be a harmful frequency. But, if all resonant frequencies are taken into account, the FFT and DMD results show 1000 Hz or higher frequencies are likely to be harmful frequencies. In order to further analyze the combustion instability of the case in this study, another advantage of the DMD technique needs to be used. As we mentioned in the previous section, the DMD method can find the damping coefficient at all resonant frequencies. Its negative value indicates stable oscillation and the positive value means unstable. As shown in Fig. 6, unstable resonant frequencies and their corresponding positive damping coefficients are shown for three cases: (a) without perturbation, (b) with 100 Hz perturbation and (c) with 1,000 Hz perturbation. In Fig. 6(a), the unstable frequency only appears above 1,000 Hz, which is called upper instability region. This is consistent with the FFT results that peak at 1029 Hz when no perturbation is applied. Therefore, it can be considered that the upper instability region is caused by the geometric characteristics of the combustion chamber itself. In Fig. 6 (b) and (c), it can be seen that after the perturbation is applied, the upper instability region becomes larger and a new lower instability region appears near at 100 Hz ~ 400 Hz. The gain of FTF shown in Fig. 2 has peaks of 100 Hz and 400 Hz. Then, the
lower instability region can be considered to be caused by the flame response. This result shows that 100 Hz with a gain peak in FTF and 1029 Hz with the largest amplitude in FFT are harmful frequencies in this case.

Fig. 7 shows all the unstable frequencies and their damping coefficients with perturbation frequencies from 0 Hz to 1000 Hz. The unstable frequencies can be divided into a lower and an upper instability regions. It shows comprehensive instability boundaries.

4. Conclusion

The DMD technique was used to analyze the combustion instability in the most unstable case from our previous study. The FTF calculated by DMD is compared with the results obtained by experiments. They are qualitatively consistent with each other with slight difference. With perturbation, the FTF results show that 100 Hz with a gain peak will be harmful. If the perturbation is not applied and all the resonant frequencies are considered, the FFT results show that the amplitude peak appears at 1029 Hz. After obtaining gains and damping coefficients of all resonant frequencies by the DMD technique, two unstable regions are identified in the combustion chamber. It is concluded that comprehensive instability boundaries can be identified by applying the DMD technique. This approach can be a viable method in finding the boundaries.

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