Large eddy simulation calculated flame dynamics of one F class gas turbine combustor

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Abstract. Thermoacoustics in modern gas turbines is always accompanied by lean premixed combustion. The flame transfer function (FTF) is an important quantity that can quantify thermoacoustics. However, the FTF is always considered as a black box and used in the final development phase. This work applied proper orthogonal decomposition (POD), which is normally used in hydraulic instability analysis. Results obtained by comparing the frequency response and mode shape indicated the flame was stable even in the presence of coherent structures in the flow field. The transfer function between the first three modes and overall heat release rate (HRR) was calculated to confirm the relationship between mode and the FTF. Results indicated that the potential risk of pulsation did not originate from flow instability.

1. Introduction
Combustors must fire at high temperatures to increase efficiency as gas turbine power is increased [1]. Striking a balance between thermoacoustics and the emission target becomes an issue [2]. The contribution of thermal NOx to emission increases at high firing temperatures. Conventional approaches for decreasing NOx emission include improving mixing by installing additional nozzles or by applying a certain mixing time [3]. The latter approach, however, delays the time of fuel flight into the flame front. This time delay would determine the phase between pressure fluctuation in the combustor and the heat release rate (HRR). The Raleigh criteria [4] state that when the HRR adds chemical energy to the pressure fluctuation within approximately the phase and the added energy is higher than the damping of the system, the combustion system may encounter thermoacoustic issues, and further structural damage might possible [5].

The current work investigates F-class flame dynamics [6, 7], specifically, the FTF of the twin swirl flame generated by hybrid burner [8]. The key issue encountered in this burner is the low-frequency pulsation experienced in part load [9, 10]. Experience has shown that frequency pulsation originates from transverse mode (T1), which will transfer upstream into the plenum and induce the T1 mode in the plenum [11, 12]. The Original Entrusted Manufacture (OEM) solved this issue in upgraded gas turbine versions by using time-lag elegance methods [13-16].

In present work, large eddy simulation (LES) is applied to study the single-head flame [17, 18]. Thus, the FTF for the network model and proper reactive field for the FEM tool could be obtained. The proper orthogonal decomposition (POD) of this flame is presented and analyzed to determine the feasibility of the current simulation.

Dealing with POD results is a perennially interesting question from the scientific perspective. Flow/flame field analysis has provided limited contribution to development work. This work attempts
to link POD results with the FTF. If the FTF has high gain, then the proposed analysis method would estimate the resulting mode shape.

2. CFD setup

2.1. Simulation domain

Figure 1. Simulation domain (left), main stage swirler (right top), axial swirler (pilot stage, right bottom).

2.2. Mesh

A hybrid mesh is generated for calculation (Figure 2). At nozzle local the source size has been reduced to less than 0.8 mm. A compromise between accuracy and LES computational cost is made. Overall, 12.4M cells are used. Three-layer prism meshes are applied for all wall boundaries.

Figure 1.
Figure 2. Overall mesh (left) and the local mesh view at the axial swirler region (right).

2.3. CFD boundary condition and setups

The baseload condition (19bar) is simulated in this work to obtain flame location, shapes, and benchmark performance. The boundary conditions are presented in Table 1. The mass flow rate is normalized based on the sum of three inlet mass flow rates.

| Boundary          | Mass flow rate (kg/s) | Temperature (K) | Species     |
|-------------------|------------------------|-----------------|-------------|
| Inlet main air    | 97.15%                 | 710             | Air         |
| Inlet main fuel   | 2.6%                   | 288.15          | Methane     |
| Inlet pilot fuel  | 0.226%                 |                 |             |

Here uses partially premixed flame with the Zimont model. In the current simulation, only pure methane is considered as fuel. GRI 3.0 is used in current paper. However, the chemical mechanism must be updated to account for the influences of high pressure. The adiabatic-type wall boundary is selected. Given that leakages are excluded from the current simulation, the averaged flame temperature is slightly higher than the real flame temperature. The flame has high tendency for stability. The bounded central difference scheme has been used for momentum discretization. The temporal update scheme and other spatial discretization schemes apply second-order upwind. The exported monitors are 1) a time series-type monitor that records volume integral of the overall HRR, and 2) snapshots with an observation window for every 10-time step.

3. Algorithm for postprocessing methods

3.1. FTF method

Broadband excitation at the burner overall inlet is used as shown in Figure 3. The discrete binary signal is applied given the simulation duration together with the energy spread in low-frequency band. The inlet excitation has the amplitude of 5% of overall air inlet mass flow rate. This is an empirical value that is sufficient for inducing a palpable flame but not flame lift or flashback [19].

The FTF is defined as follows:

\[
FTF = \frac{\dot{q}/\dot{\phi}}{\dot{m}/m}
\]  

The FTF is calculated using regression method, which is also the standard algorithm of frequency response function [20].
3.2. POD method

The statistical method principal component analysis (PCA) is also called POD in fluid dynamics. The reactive swirl flows have been analyzed based on the correlation between POD modes and the chemical represented fields.

In current paper, since dataset type in PCA is unlimited, flame data are counted only inside the data matrix. As shown below, dataset is collected along simulation time ($t = 0, 1, ..., N$) and assembled in rows. The matrix represents the flame in spatial dimension. Current paper selects HRR, which shows high concentrate at flame fronts.

\[
X_0 = \begin{bmatrix}
\vdots & \vdots & \vdots \\
\chi^0 & \chi^1 & \chi^N \\
\vdots & \vdots & \vdots 
\end{bmatrix}
\]  

(2)

Do the standardize for $X_0$ and obtain $M$. This step removes the mean field and make the matrix in the center of space. In current paper, after the inlet excitation has been applied for ten flow-through-time, the snapshots are recorded with 0.1ms duration. There are totally 1001 snapshots recorded during the excitation LES simulation. Stack the first 1000 snapshots in column direction with the shape described above.

Single value decomposition (SVD) is applied. It computes the eigenvalues and corresponding eigenvectors of $M$. Then sorting the eigenvalues in the decrease manner, and so do the corresponding eigenvectors.

4. Results

4.1. Ensembled LES results

LES was enabled from reactive RANS results. After 0.05s flow time, fluctuated flame is generated in LES. Then LES has been stopped and inlet mass excitation has been enabled. After 0.05s flow time, the reactive field has been collected every 0.1ms. The observation window has been limited as in Figure 4.

![Figure 4](image)

**Figure 4.** Instantaneous contour plot of product formation rate, red line indicates the location of observation window.

Product formation rate represents the location where mixture fluids turn into products. In this work, product formation rate is selected as the parameter to represent the flame front, and its value represents the HRR. The ensemble-averaged results are shown in Figure 5.
Above figures shows that

- Two main flame fronts exist. The short flame front located at the center of the combustor has low HRR, which is attributed to the local mixture fraction from the center swirler. The main flame is generally long and has high HRR.
- Fuel is highly concentrated on the outer layer of the main flame because the main fuel streams from the nozzles close to the outer diameter are undergoing insufficient mixing due to the absence of local mixing. Those fuel streams flow downstream into the flame front.
- The swirl number (SN) is high at the outer branch of main flame, and low at the inner branch of main flame. However, there is no diffusor angle at the burner exit. Thus, streamwise vortices cannot induce upward velocity components, there is no vortex breakdown sign. In the contrast, the inner branch of the main flame has low swirl number but free space to flow radially outward, the bubble type CRZ happens locally.
- The pilot flame is short and penetrates the inner layer of the main flame. It stabilizes the inner layer of the main flame. This is the NOx emission source as indicated by the local high mixture fraction and negligible presence of mixing length.

### 4.2. FTF results

The calculated SISO FTF is presented in Figure 6. The overall gain is less than 1, which fits the field observation that there is reported pulsating issue in baseload. This result indicates that under the current operating condition, the flame does not provide contributions as the acoustic energy source.

However, if the error bar is considered, then the 50 Hz band shows a potential high-gain risk, which indicates that the flame might not stable in this frequency band. Two other high-gain frequency bands
appear near 150 and 240 Hz. The gain in those two frequency bands, however, are lower than 1. The phase shape indicates convective propagation before 300 Hz.

4.3. POD results

Figure 7 shows the first three POD modes and corresponding time coefficients and frequency bands. The first three modes show a clear frequency band at 50 Hz. The first two modes indicate that two shapes combine at the outer ring of the main flame: One mode is shedding type streamwise fluctuation. The other mode locates at the same location but has a radial shape.

4.4. Coherence of flame dynamics with POD modes

Present work attempted to calculate the coherence between POD time coefficients and the generated HRR. Given that the frequency response of the signal used in the calculation is not limited, calculating the transfer function in the same manner as the FTF is possible. The transfer function between the HRR and the chemical-dominated POD modes at the observation plane are compared in Figure 8.

The shape of the transfer function of mode 2 is like that of the overall FTF. High gain is observed at 50 Hz. The corresponding mode is attributed to the un mixed fuel streams from the outer layer of the main swirler vanes. Tuning nozzle shape would help reduce such an effect.
5. Conclusions

This work obtained the LES results for one F-class gas turbine combustor. Analysis focuses on three issues: 1) a method for identifying the potential risks of thermoacoustics; 2) a method for opening the black box of the FTF; and 3) the verification of the coherent structures of the flow or flame as the origins of high FTF gain.

Numerous works have validated the appropriateness of the FTF for describing the risk of thermoacoustics. The FTF shows high gain at 50, 150, and 240 Hz. Nevertheless, the results also indicate that no frequency band has high gain that might result in the risk of thermoacoustic. Snapshots are collected and processed by using POD. The postprocessing results show that the fluctuating HRR originates from the root of the main flame. The time coefficients of the modes are subjected to similar transfer functions with HRR to determine if the POD modes are cause of thermoacoustic issue. Results show that although flow/flame coherent structures exist and POD time coefficients show frequency bands, they do not result in pulsation risks.

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