Large Eddy Simulation of Combustion Instability in Gas Turbine Engines

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Combustion Instability Example

Gas Turbine Configuration

Burner assembly damaged by combustion instability and new burner assembly
What is Combustion Instability?

- Combustion instability is characterized by large-amplitude pressure oscillation in the combustor chamber. It is usually a result of unsteady flow and/or unsteady combustion heat release rate.

**Consequences**

- Component vibration
- Enhanced heat transfer of combustor walls
- Fatigue failure of system component
- Unstable thrust
The combustor walls are usually perforated, cooling air is injected through the perforates to protect the combustor wall from high temperature. The perforation is also proved to have obvious attenuation effect on the pressure fluctuation in the chamber. However, the large number and the small size of holes is too prohibitive to allow full CFD calculation.

Perforated combustor wall and its working conditions [1]

Aims and Objectives

• Validate CFD’s capability in predicting pressure fluctuation in unstable flow

• Find a method to account for the perforated walls rather than solving for the tiny holes

• The Final Aim: Complete CFD simulation of gas turbine combustors

• Background: Experimental design is too expensive and time-consuming
Validation Case for LES

The geometry of PRECCINSTA and measurement position of velocities [2]

Numerical Setup in STAR CCM+

- Number of cells: 1.2 million, average cell size: 1mm
- Models: URANS with K-Epsilon turbulence model, EBU combustion model
  - LES with Wales sub-grid model, thickened flame model
- Chemical Kinetics: Methane two-step reaction mechanism
- Temporal Scheme: Bounded Seconded Order Implicit scheme
- Spatial Discretization Method: Second Order Upwind
- Boundary Conditions: Mass flow inlet, Constant Pressure outlet
- Fuel/Air ratio: 0.7
Validation Results

Mean axial velocity profiles at five cross sections of different height in the combustor.
Validation Results

RMS value of axial velocity fluctuation profiles at five cross sections of different height in the combustor
Instability Mode Prediction

Dominant pressure fluctuation frequencies

<table>
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<th>Acoustic mode</th>
<th>Non-reacting flow</th>
<th>Reacting flow</th>
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<td>580Hz</td>
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CFD results of pressure fluctuation at different frequencies in the combustor. (left: non-reacting flow; right: reacting flow)
Mendez et al. [1] in 2008, proposed a uniform wall model to account for effusion cooling effect. This model is rather complex and hard to integrate with CFD software. Its acceptability to reflect the noise attenuation effect is still open for validation.

Jourdain et al. [3] in 2014, developed a model based on URANS solver but it would not work with LES solver which we will use to predict the pressure fluctuation.

Our Approach

- Use of porous material model to represent thin perforated wall.
  - The detailed geometry of the small holes is ignored while the porosity, thickness, and flow resistivity remains important.
  - Porous material model is designed for uniform and highly porous materials, Modification need be done.

- Navier-Stokes equation:
  \[
  \frac{\partial (\rho u_i)}{\partial t} + \text{div}(\rho u_i u) = -\frac{\partial p}{\partial i} + \text{div}(\mu \text{grad} u_i) + S_u
  \]

- Navier-Stokes equation for porous material:
  \[
  \frac{\partial (\chi \rho u_i)}{\partial t} + \text{div}(\chi \rho u_i u) = -\chi \frac{\partial p}{\partial i} + \text{div}(\mu \chi \text{grad} u_i) + \chi (S_u + S_p)
  \]

- The porous media body force term:
  \[
  S_p = -(P_v + P_i \cdot v) \cdot v
  \]

where \( \chi, P_v, P_i, v \) denote porosity, viscous and inertial resistivity coefficient and velocity respectively.
Validation Case 1

- Pure noise absorption effect of perforated panel absorber was experimentally, numerically and analytically studied and the results were compared.

Experimental setup for measuring the noise absorption effect of the perforated plate

Mesh generated for the impedance tube
Numerical Setup in ANSYS FLUENT

- Cells number: 91,000
- Models: Laminar flow, porous material model
- Temporal scheme: Bounded Second Order Implicit scheme
- Spatial discretization method: Second Order Upwind
- Boundary condition: Pressure far-field white noise inlet
Pure Noise Absorption Results

- "A&S" and "Maa’s" in the graph represent the result acquired by Atalla and Sgard’s empirical formula and Maa’s theory for predicting MPP absorption effect.

Absorption coefficients of the perforated panel absorbers
(left: porosity=0.38%, right: porosity=1.23%)
The cooling air going through the perforation is called bias flow. Bias flow has significant effect on the pressure fluctuation absorption property of the perforated plate. In this validation case, bias flow is included in addition to the pure pressure fluctuation.

Experimental setup for measuring noise absorption effect of the perforated plate with bias flow [4]

The results tell us, different bias flow velocities bring different reflection coefficients for the same perforated plates. Porous material model can provide good prediction accuracy.

Reflection coefficients of the perforated panel with bias flow (left: bias flow velocity=2m/s; right: bias flow velocity=5m/s)
Future Work

- Apply this approach to the cases with swirling cold and reacting flow in real combustors

Gas turbine combustor configuration (obtained from Technical Lecture - Siemens Power Gas Turbines, held in Hull University, 17 Oct. 2012)
Thank you

Any Questions?