Large Eddy Simulation of Azimuthal Instability in a Model Annular Gas Turbine Combustor

Zhi X. Chen & N. Swaminathan

University of Cambridge
Department of Engineering
Outline

• Background – thermoacoustic instabilities & azimuthal mode

• LES formulation and combustion modelling

• Simulation of a model annular combustor
  ▶ Single sector – grid sensitivity and flame transfer function (ext. forcing)
  ▶ 12 burner full annular – self-excited oscillations

• Summary and future work
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Thermoacoustic instabilities

• Fuel lean combustion is prone to thermoacoustic instabilities in gas turbines.

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Image sources:
Thermoacoustic instabilities

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Azimuthal mode

- Azimuthal mode instabilities are more complex, damaging and not yet well understood.

Image sources: 1. WSJ research; Rolls Royce
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Azimuthal mode

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Smaller acoustic length compared to longitudinal modes

Higher frequency and amplitude

LES → Onset of azimuthal instabilities

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LES and combustion modelling

- 3D filtered N-S equations (mass, momentum and energy) are solved
- Compressibility effects are considered: pressure work heating, equation of state

A flamelet model for partially premixed combustion

Chemistry tabulation (GRI 3.0) using a collection of premixed flamelets

\[ \varphi = \mathcal{F}(Z, c) \]

First two moments are transported along with enthalpy

\[
\overline{\rho} \frac{D\overline{\varphi}}{Dt} = \nabla \cdot \left[ \left( \mu + \frac{\mu_t}{Sc_t} \right) \nabla \overline{\varphi} \right] + \overline{S^+_{\varphi}} - \overline{S^-_{\varphi}}
\]

\[ \overline{\varphi} = \left\{ \overline{Z}, \overline{Z^2}, \overline{c}, \overline{c^2}, \overline{h} \right\}, \]

\[ \overline{S^+_{\varphi}} = \left\{ 0, 2 \frac{\mu_t}{Sc_t} \overline{| \nabla \overline{Z} |^2}, 2 \frac{\mu_t}{Sc_t} \overline{| \nabla \overline{c} |^2} + 2 \left( c \overline{\omega_c} - \overline{c} \overline{\omega_c} \right), \frac{D\overline{\rho}}{Dt} \right\}, \]

\[ \overline{S^-_{\varphi}} = \left\{ 0, 2 \overline{\rho} \overline{cZ}, 0, 2 \overline{\rho} \overline{cZ}, 0 \right\}. \]

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Cambridge/NTNU gas turbine model annular combustor

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Refs:
Single sector – grid sensitivity and flame transfer function

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Single sector – grid sensitivity and flame transfer function

Grid sensitivity and flame transfer function

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\[ f = 1800 \text{ Hz} \] (1st azim. mode)

\[ U_b = 15 \text{ m/s} \]

\[ U = A U_b \sin(2\pi ft) \]

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Single sector – grid sensitivity and flame transfer function


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U_b = 15 \text{ m/s} \\
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FTF = \frac{\dot{q}'/\bar{q}}{U'_0/U_0} = G(\omega) e^{i\Phi\omega}

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\[
\dot{q} = \int_V HRR(x, t) \, dV
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Single sector – grid sensitivity for temperature and velocity fields

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$x/D = 2$

Unforced
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- \( x/D = 2 \)
- \( x/D = 1 \)
- \( x/D = 0.5 \)

Unforced

Mean axial velocity

Mean temperature
Single sector – grid sensitivity for flame transfer function

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\[ p'/\bar{p} < 1\% \]

Two excitation amplitudes are tested: 5% & 10%

\[ U = A \, U_b \, \sin(2\pi ft) \]

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For \(A = 0.05\):

For \(A = 0.1\):

Fluctuation vs. time for different cases.
Single sector – grid sensitivity for flame transfer function

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\[ \text{Gain} \]

\[ \text{Phase/\pi} \]

\[ A [-] \]
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Computed pressure signals in the plenum tubes

- Longitudinal mode
- Transition
- Azimuthal mode

![Diagram showing pressure signals in the plenum tubes](image)
Computed pressure signals in the plenum tubes

- Longitudinal mode
- Transition
- Azimuthal mode

![Graph showing pressure signals with markers for longitudinal, transition, and azimuthal modes.](image)
Computed pressure signals in the plenum tubes

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Graphs showing pressure signals over time with different modes indicated.
Computed pressure signals in the plenum tubes

Computational cost: 48 hrs on wall-clock for 0.1s using 1248 cores, 20M cells  \(\rightarrow\) 900 kAU
Longitudinal mode
Azimuthal mode
Longitudinal -> Azimuthal mode transition in frequency domain

![Graph showing longitudinal to azimuthal mode transition in frequency domain.](image-url)
Heat release rate fluctuations and acoustic mode structure
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Summary and future work

• Azimuthal instability in a model annular combustor is studied using LES

• LES are performed in two steps:
  ▶ Single sector – grid sensitivity and flame transfer function (external forcing)
  ▶ 12 burner full annular – self-excited oscillations: transition from longitudinal to azimuthal mode

• Projected future works:
  ▶ Analyse the LES data to study mode switching
  ▶ Non-adiabatic simulations
Thank you for listening!

Questions?