SAC Dynamics

Technical Analysis of Combustion Dynamics in Single Annular Combustor (SAC) Sectors

1. Introduction to Thermo-Acoustic Instabilities

Thermo-acoustic instabilities represent a significant obstacle in the advancement of lean-premixed gas turbine technology. These phenomena are governed by the constructive coupling between unsteady heat release ($\dot{q}'$) and acoustic pressure oscillations (p'), as described by the **Rayleigh Criterion**.

When these fluctuations occur in phase, the acoustic field extracts energy from the combustion process, leading to high-amplitude pressure pulsations. This is summarized by the Rayleigh integral:

$$\int_0^T p'(t) \cdot \dot{q}'(t) \, dt > 0$$

In modern swirl-stabilized systems, these instabilities are driven by:

- **Feed-coupling mechanisms:** Equivalence ratio oscillations at the burner inlet.
- **Hydrodynamic instabilities:** Vortex shedding and swirling flow periodicity.

2. Experimental Rig Architecture

The investigation used an atmospheric test facility replicating a SAC sector. Key components include:

- **Heater:** 72 kW inline electrical heater (preheat up to 700 K).
- **Conditioning Chamber:** 154.1 mm (6.065 in) internal diameter; 610 mm (24 in) length.
- **Burner:** Double swirler cup with counter-rotating radial swirlers.

Experimental Boundary Conditions

Parameter	Operating Range	Increments
Inlet Air Temperature (T_{inlet})	$200°\text{F}$ to $600°\text{F}$	$\Delta T = 200°\text{F}$
Swirler Pressure Drop (ΔP)	2%, 4%, 6% of P_{atm}	Fixed Steps
Max Air Mass Flow Rate	0.11 kg/s	-
Equivalence Ratio (Φ)	0.25 to Rich Limit	$\Delta\Phi = 0.05$

3. Measurement Methodology

A suite of high-bandwidth sensors resolved the thermo-acoustic coupling:

- **Dynamic Pressure:** Four **PCB 112A05** transducers mounted along the liner (starting $25\ \mathrm{mm}$ downstream of the swirler).
- **Optical Diagnostics: PHANTOM V7.3** high-speed camera ($6000\ \mathrm{fps}$) capturing CH^* chemiluminescence.
- **Acoustics:** AKG D112 microphone positioned $1\ \mathrm{foot}$ from the exit.
- **Thermal:** Type K (inlet) and Type B (exit) thermocouples to determine local sound speeds (c).

4. Primary Acoustic Modes and Flame Structures

Spectral analysis identified three primary frequency bands:

Mode	Frequency	Range (Φ)	Driving Mechanism	Flame Anchor
Lean Mode	$\approx 280\ \mathrm{Hz}$	$0.25 \leq \Phi \leq 0.38$	Shear layer oscillations	Swirler Exit / Dome
Rich Mode	$\approx 420\ \mathrm{Hz}$	$\Phi \geq 0.42$	Dilution jet interaction	Downstream Wakes
Chamber Mode	$\approx 600\ \mathrm{Hz}$	Variable	Longitudinal quarter-wave	Global

Fuel-Lean vs. Fuel-Rich Transitions

- **Lean Regime ($280\ \mathrm{Hz}$):** The flame is contained in the dome. High-speed imaging reveals a circular unsteady heat release pattern.
- **Rich Regime ($420\ \mathrm{Hz}$):** As $\Phi > 0.42$, the dome becomes too rich. The reaction zone migrates downstream to anchor in the wakes of the primary dilution jets.

5. Aerodynamic Performance

Laser Doppler Velocimetry (LDV) shows a robust **Central Recirculation Zone (CRZ)**. The $280\ \mathrm{Hz}$ mode is anchored in the shear layer between the outer swirling jet and the inner recirculation zone.

In the fuel-rich regime, the instability is dominated by the vortex structures associated with dilution air penetration.

6. Parametric Sensitivity

Inlet Temperature (T_{inlet})

Increasing T_{inlet} increases the frequency of both modes. This follows the relationship for the speed of sound:

$$c = \sqrt{\gamma RT}$$

As temperature rises, the sound speed increases, reducing acoustic travel time across the combustor's characteristic lengths.

Pressure Drop (ΔP)

- **First Mode ($280\ \mathrm{Hz}$):** Frequency is directly proportional to convective air speed. Increasing ΔP from 2% to 6% causes a distinct upward frequency shift.
- **Second Mode ($420\ \mathrm{Hz}$):** Relatively insensitive at $4\text{--}6\%$. At 2%, frequency drops due to slower fuel-air mixing reducing local flame temperature.

7. Quantitative Results and Phase Analysis

Fast Fourier Transform (FFT) of chemiluminescence sequences mapped the phase relationship between heat release and acoustics:

1. **Circumferential Interaction ($280\ \mathrm{Hz}$):** A phase difference of 180° was measured between the top and bottom acoustic energy "spots" in the dome.
2. **Dilution Jet Interaction ($420\ \mathrm{Hz}$):** A 360° phase shift is observed around the dilution air jets, representing a wave propagating from the hole exit to the impingement point.

> **Conclusion:** The system undergoes a critical "mode shift." Transitioning from lean to rich operation moves the driving mechanism from dome aerodynamics to dilution system interactions.