HIGH-FREQUENCY TRANSVERSE COMBUSTION INSTABILITIES IN LOW-NOX GAS TURBINES (DE-FE0031285)

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CREATING THE NEXT®
Motivation for Research

- Combustion dynamics are a critical challenge in high efficiency gas turbines
  - Transverse, “screeching” instabilities are increasingly problematic

- **Target architecture** → Multi-nozzle can combustor configuration with interacting flames
  - Extensive research and literature to address longitudinal mode instabilities with acoustically compact flames

- Focus of the proposed project → High-frequency transverse combustion instabilities in multi-nozzle can combustor configurations.

Realistic multi-nozzle experiments and high frequency modeling capabilities needed
DISTINGUISHING FEATURES OF HIGH FREQUENCY, TRANSVERSE INSTABILITIES

- Acoustic wave motions perpendicular relative to main flow direction
  - intrinsic non-axisymmetric excitation
  - No direct net mass flow modulation of reactants (although indirect effect can be large, $F_{TL}$ path on chart)
- Wave can be spinning or standing; nodal lines can move
- Acoustic wavelength of the order of heat release zone extent
  - Flame not compact; its spatial distribution matters
  - E.g., ideal heat release for 1-T mode has spatial integral of zero
EXPERIMENTS AND DATA ANALYSIS

TASK 2 ACCOMPLISHMENTS
RESEARCH TASK 2

TASK 2.1 – EXPERIMENT

- D=29 cm combustor → capture accurate high-frequency acoustics
- Multiple nozzles → capture flame-flame interactions.
- Optical accessibility using quartz → spatio-temporal flow and flame characterization
- Ability to vary heat release distribution in radial and azimuthal direction → 3 fuel circuits (P, O1, O2)
RESEARCH TASK 2
TASK 2.2 – MODAL DYNAMICS

• Modal nature of transverse instabilities (e.g., $m = 1$ transverse mode)
  • Standing vs spinning: characterized by $SR$
    
    Standing wave ($SR = 0$)
    Spinning wave ($SR = 1$)
    Mixed wave ($SR = 0.5$)

• Orientation of anti-nodal line: characterized by $\varphi_{FG}$ ($\theta_a = -\frac{\varphi_{FG}}{2}$)
  
  Horizontal ($\varphi_{FG} = 0$)
  Vertical ($\varphi_{FG} = \pi$)
  Func of time ($\varphi_{FG} = \varphi_{FG}(t)$)
Pressure signal is harmonically oscillating.
- Magnitude (envelope) of pressure signal is oscillating. → Quasi-periodicity
- Spin ratio and phase difference (anti-nodal line) are oscillating.
  → The wave is predominantly a standing wave ($SR = 0$), but it periodically oscillates around it.
  → Anti-nodal line is oscillating around its averaged location (reason for pressure magnitude oscillation).
  → Modal nature is periodically oscillating.
✓ Developed multi-nozzle facility with radial/azimuthal fuel staging capabilities

✓ Identified range of conditions with 1-T mode, with various dominant standing and spinning wave dominant conditions

✓ Phase portraits show different types of dominant attractors, leading to substantively different pressure sensor measurements

✓ Magnitudes of pressure and heat release fluctuations are positively correlated, and their phase difference satisfies the Rayleigh criterion.

✓ Non-uniform azimuthal fuel staging reduces the overall instability amplitude

✓ Non-uniform azimuthal fuel staging provides a standing wave with anti-node at a fixed location
MODELING THE DYNAMICS DURING HIGH-FREQUENCY INSTABILITIES

TASK 3 ACCOMPLISHMENTS
High-frequency $\rightarrow$ Non-compact flames

- Cannot use global heat release dynamics
- Acoustic energy dynamics

A necessary condition for the Rayleigh Integral:

$$ RI = \int t \int V p_1 \dot{q}_1 dV dt > 0 $$

- Explicit flame dynamics
- Normalized Rayleigh Index
RESEARCH TASK 3.1
SUMMARY OF PRIOR RESULTS

- Stability for low-frequency compact flames: global flame transfer function
- Stability for high frequency non-compact flames: Rayleigh index
- Prior modeling studies on single flames
  - Axisymmetric mean flames centered in combustor
  - Axisymmetric mean flames offset from combustor axis
  - Non-axisymmetric mean flame effects
  - Comparison to induced axial excitation

Radial modes – always unstable! (1,1) – islands of stability

Outward radial offset increases stability
Azimuthal offset increases stability
Prior work was for single flames only

What about multiple flames/multi-nozzle systems?

- How to optimally position nozzles for stability?
- How to optimally operate given nozzles for stability?
RESEARCH TASK 3.1

NOZZLE POSITION OPTIMIZATION FOR 1-T MODE

For a fixed set of flame/flow parameters, what is the optimal positioning for the multiple nozzles

\[ \hat{Z}_{TL} = 10.0, \quad \angle \hat{Z}_{TL} = 0 \]

\[ \hat{Z}_{TL} = 10.0, \quad \angle \hat{Z}_{TL} = \pi/2 \]
For a fixed set of nozzle locations, what is the optimal operating flame/flow parameters

\[ |\hat{Z}_{TL}| = 1.0, \quad \angle \hat{Z}_{TL} = 0 \]

6 equally distributed nozzles, showing only 2-4
RESEARCH TASK 3.1
OPTIMIZATION STUDY TAKEAWAYS

➢ Nozzle optimization study (fixed operating parameters, move nozzles around)
   o 1-R mode → minimal RI at $0.6R_C$ (pressure node) → nozzles distributed symmetrically
   o 1-T mode → non-axisymmetric → radial offset depends on angular location in mode
     ▪ Optimal distribution unlike conventional symmetric nozzle placements.
     ▪ Indicates lowest possible RI requires drastically different nozzle placements.

➢ Parameter optimization study (fixed nozzle placements, optimize operating parameters)
   o 1-R Mode → optimal flame angle/swirl → large parameter space with negative RI.
   o 1-T mode (6 around 1) → 4 different operating parameters for outer nozzles → similar to nozzle staging.

➢ Additional considerations
   o Fixed mode shape relative to the nozzle placements (extend to dynamic mode-shapes)
   o Only axisymmetric flames (on-going work to extend to non-axisymmetric flames)
   o Vortical flow fluctuations → nozzle flow/swirler optimization for hydrodynamics/vortical-acoustic interactions that minimize RI → on-going work.
RESEARCH TASK 3.2
HYDRODYNAMIC STABILITY MODELING

- Swirling flows and flames in annular geometries exhibit range of topologies.
- Complex flow dynamics strongly affect flame stabilization and shape:
  - Flame aerodynamically stabilized in front of vortex breakdown stagnation feature.
  - Flame anchoring position highly unsteady, in contrast to stabilization at edges/corners.
  - Response of flame to imposed disturbance is materially different.
- Under what circumstances can such flames exist?
  - Not always observed; flames may blowoff directly without reverting to a “free floating” configuration
  - Flow must have interior stagnation point
When are certain families of solutions possible?

What types of solutions are possible?
RESEARCH TASK 3.2
HYDRODYNAMIC STABILITY MODELING

- Nonlinear bifurcation analysis
  - Saddle-node bifurcations -> hysteresis
  - Hopf bifurcations -> limit cycles

*Low swirl: wake regime*
Nonlinear bifurcation analysis
- Saddle-node bifurcations -> hysteresis
- Hopf bifurcations -> limit cycles

Strong swirl: vortex breakdown regime

$|m| = 2$ limit cycle

$|m| = 1$ limit cycle
Nonlinear bifurcation analysis

- Saddle-node bifurcations -> hysteresis
- Hopf bifurcations -> limit cycles
- Introduce lean-premixed reactions 
  → add additional, coupled flame dynamics (e.g. flashback)
Flame shape and stabilization cannot be predicted reliably without excellent understanding of underlying fluid mechanics.

Annular swirling flows exhibit strong hysteresis and three-dimensionality, influencing both flame position and nature of flow disturbances exciting the flame.
KEY ACCOMPLISHMENTS FROM EXPERIMENTS

✓ Designed a multi-nozzle can combustor experiment with
  • Radial/azimuthal fuel staging to control modal dynamics
  • Multiple pressure taps to characterize multi-dimensional transverse mode shapes
  • Chemiluminescence characterization for heat release

✓ Established new data analysis methods to understand the dynamic nature of the transverse modes through statistical, correlation and Fourier based analysis

✓ Understood correlation between heat release and excited mode during high-frequency transverse instabilities through simultaneous flame-pressure measurements

✓ Investigated the effects of azimuthal fuel staging on instability amplitude and its modal nature
KEY ACCOMPLISHMENTS FROM MODELING

✓ Flame response modeling framework
  ✓ Response to Direct Acoustic Excitation from natural transverse modes & Induced axial excitation
  ✓ Multiple flame configurations- axisymmetric, non-axisymmetric, variable flame location in combustor
  ✓ Analyzed mode amplification (non-dimensional growth rate) for different flames to different modes to understand stability bands
  ✓ Nozzle and Parameter optimization studies for individual nozzle distribution and operation

✓ Hydrodynamic stability modeling
  • Internal tool developed to study hydrodynamic stability in reacting flows using FreeFEM++
  • Modeling of swirling flow instabilities