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Georgia Tech

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

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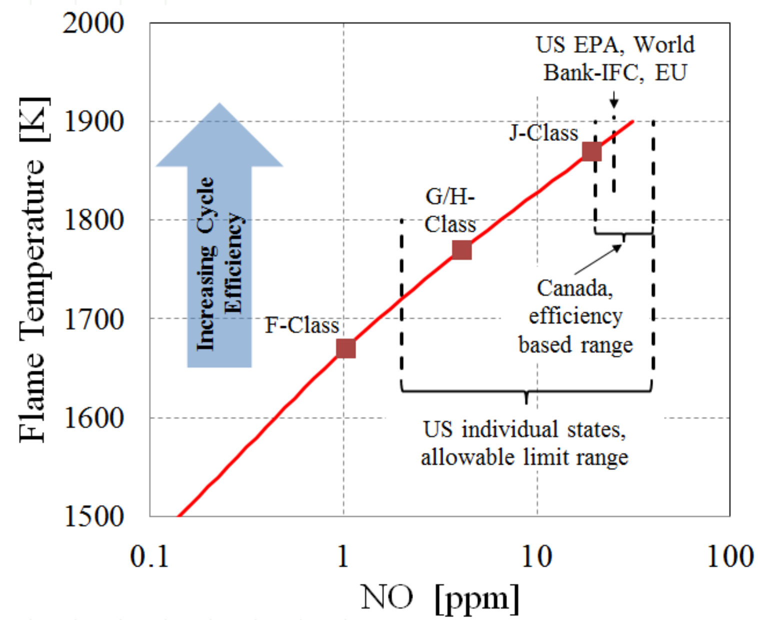
MOTIVATION FOR RESEARCH

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

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

- <u>Focus of the proposed project</u> → **High-frequency transverse combustion instabilities in multi-nozzle can combustor configurations.**

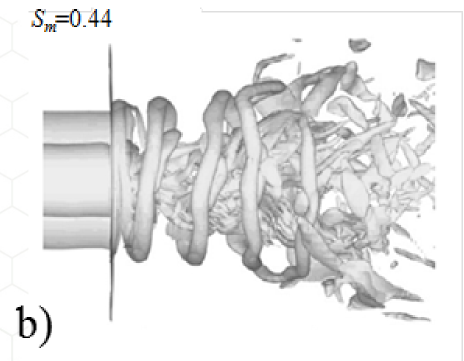


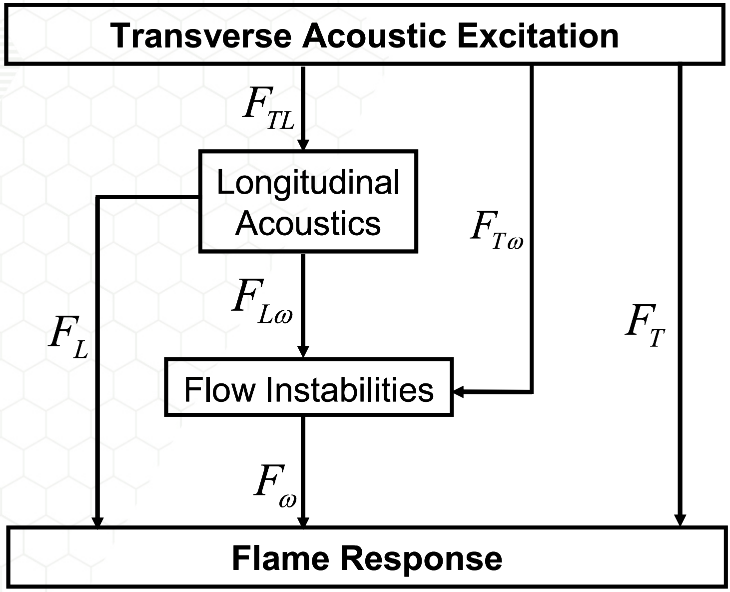
Realistic multi-nozzle experiments and high frequency modeling capabilities needed

DISTINGUISHING FEATURES OF 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

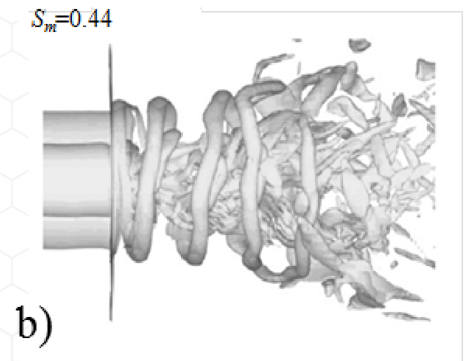
O'Connor, L., Acharya, V., Lieuwen, T., "Transverse Combustion Instabilities: Acoustics, Hydrodynamics, and Flame Dynamics", *Progress in Energy and Combustion Sciences*, Vol. 49.

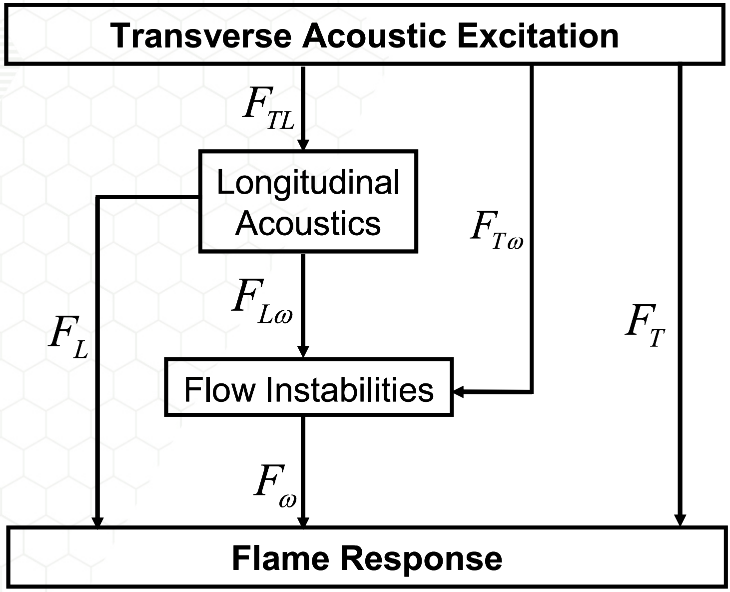




DISTINGUISHING FEATURES OF HIGH FREQUENCY, TRANSVERSE INSTABILITIES

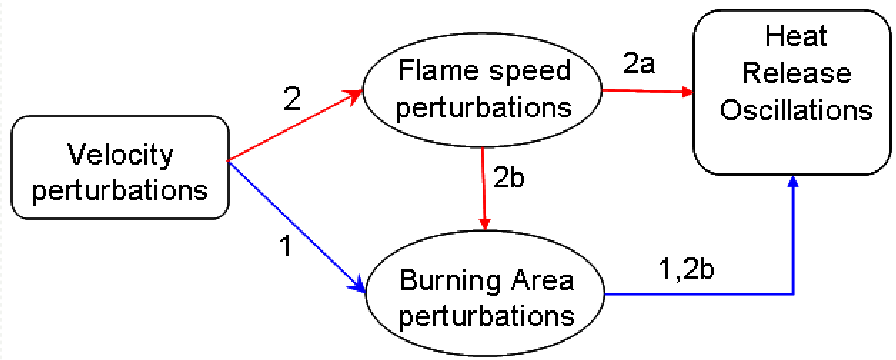
- Acoustic wave motions perpendicular relative to main flow direction
  - intrinsic non-axisymmetric excitation
  - No direct net mass flow modulation of reactants (although indirect effect can be large, F_{TL} path on chart)
- Wave can be spinning or standing; nodal lines can move
- Acoustic wavelength 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

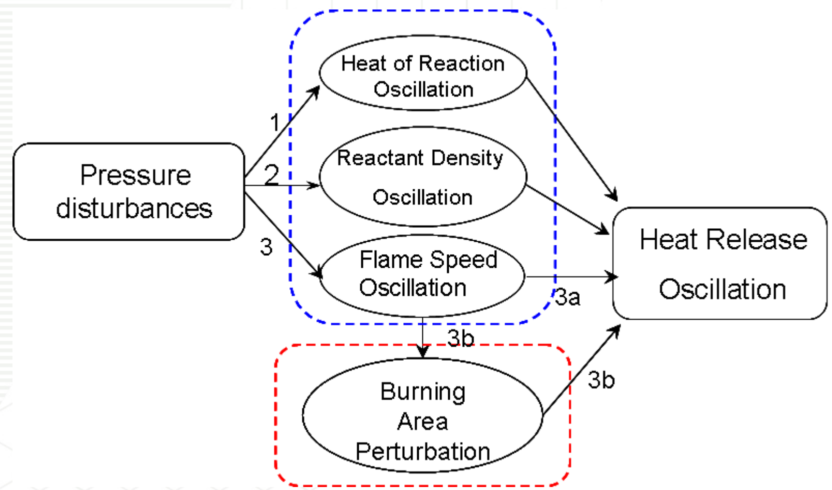




FLAME RESPONSE PATHWAYS

- Coupling of acoustics, flow hydrodynamics and chemical kinetics creates multiple pathways to drive heat release oscillations
  - Velocity fluctuation driven
  - Equivalence ratio fluctuation driven
  - Pressure fluctuation driven





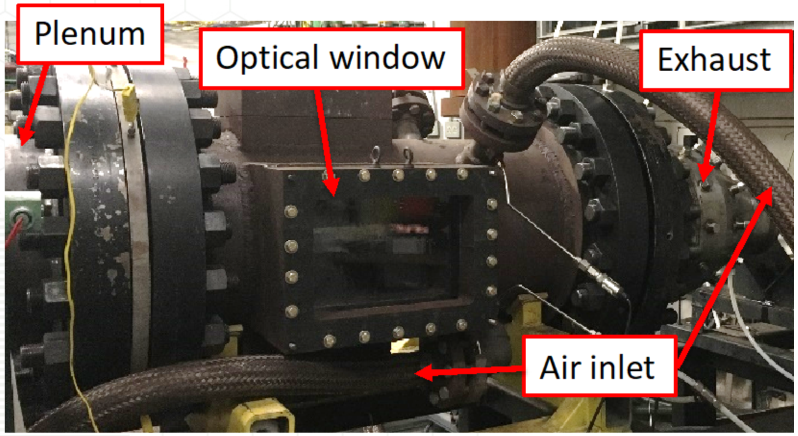
KEY ACCOMPLISHMENTS FROM EXPERIMENTS

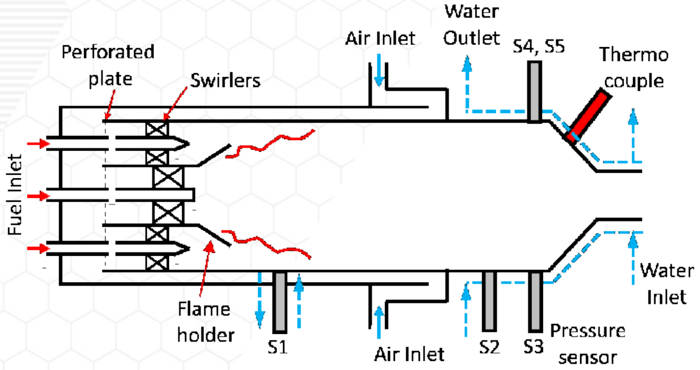
✓ Designed a multi-nozzle can combustor experiment with

- 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

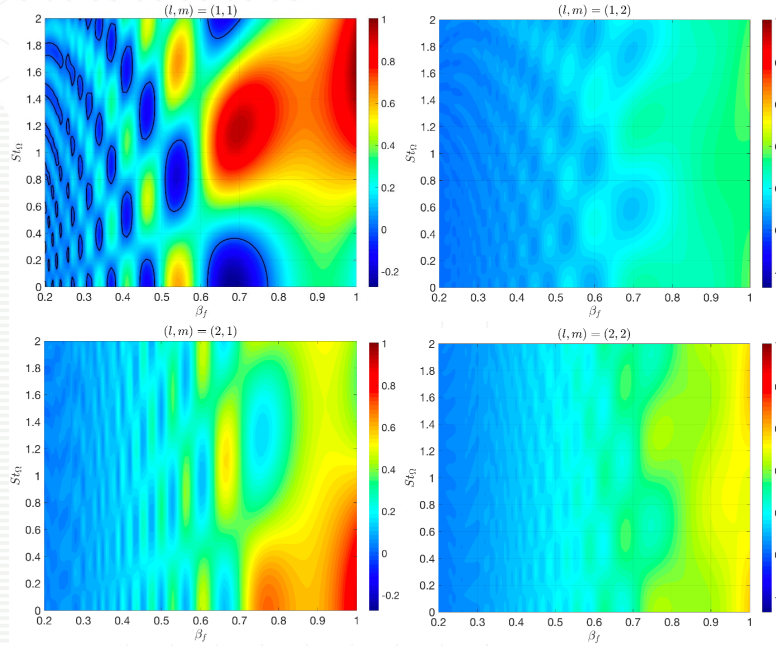
✓ Understood correlation between heat release and excited mode during high-frequency transverse instabilities through simultaneous flame-pressure measurements

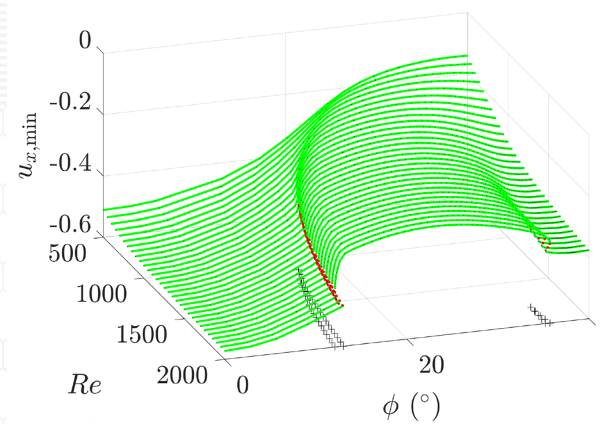




KEY ACCOMPLISHMENTS FROM MODELING

- ✓ Flame response modeling framework for 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
- ✓ Hydrodynamic stability modeling
  - Internal tool developed to study hydrodynamic stability in reacting flows using FreeFEM++
  - Modeling of swirling flow instabilities
- ✓ Pressure coupling mechanism
  - Effects of pressure fluctuations on flame response through reacting 1D simulations





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EXPERIMENTS AND DATA ANALYSIS FOR HIGH-FREQUENCY INSTABILITIES

TASK 2 ACCOMPLISHMENTS

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RESEARCH TASK 2

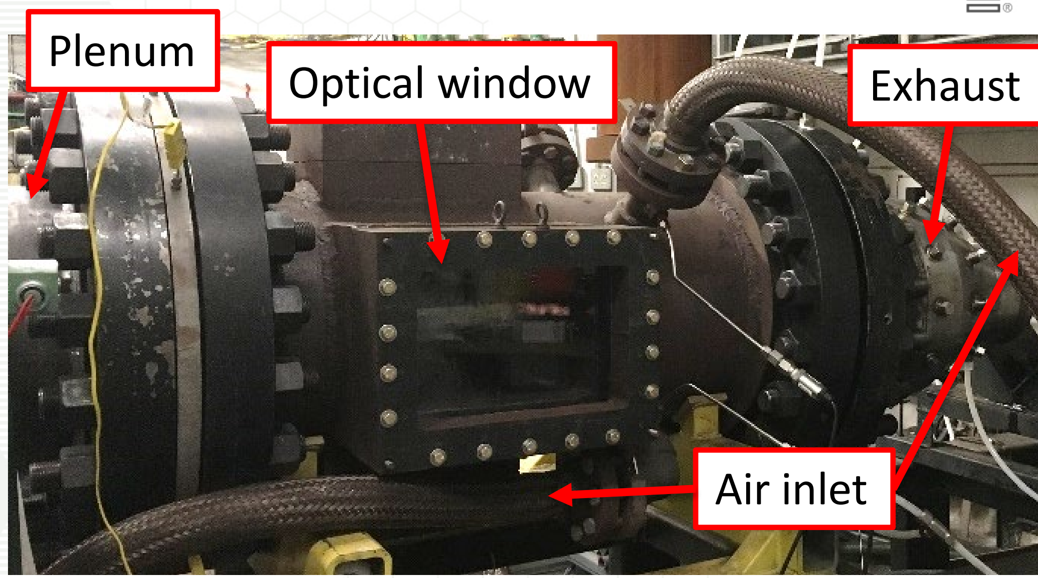
TASK 2.1 - EXPERIMENT

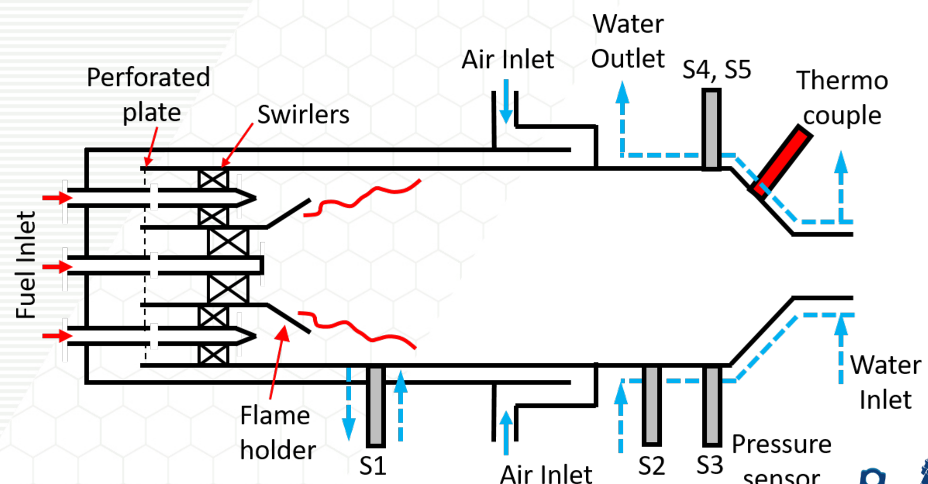
- D=29 cm combustor
  → capture accurate high-frequency acoustics

- Multiple nozzles
  → capture flame-flame interactions.

- Optical accessibility using quartz
  → spatio-temporal flow and flame characterization

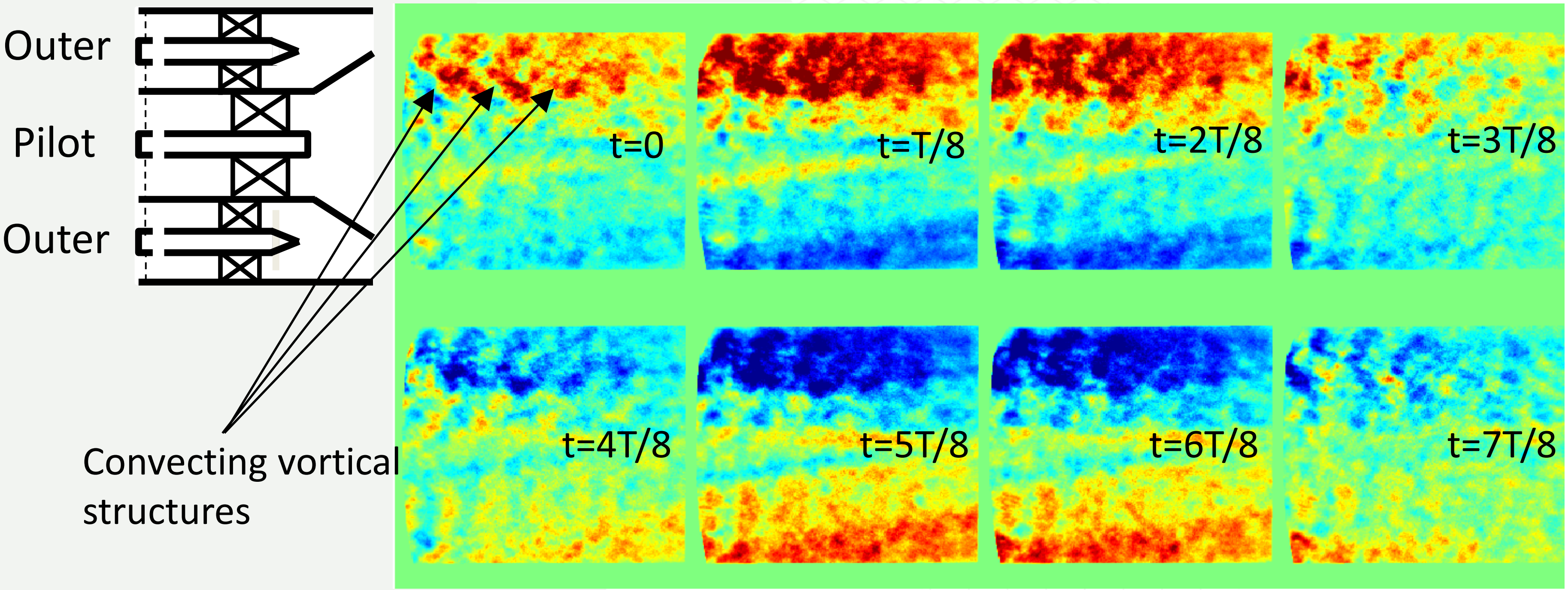
- Ability to vary heat release distribution in radial and azimuthal direction
  → 3 fuel circuits.





RESEARCH TASK 2

TASK 2.3 - FLOW AND FLAME CHARACTERIZATION



CH* phase averaged images

- Out-of-phase oscillations between the top and the bottom
- Observed coherent structures convecting downstream

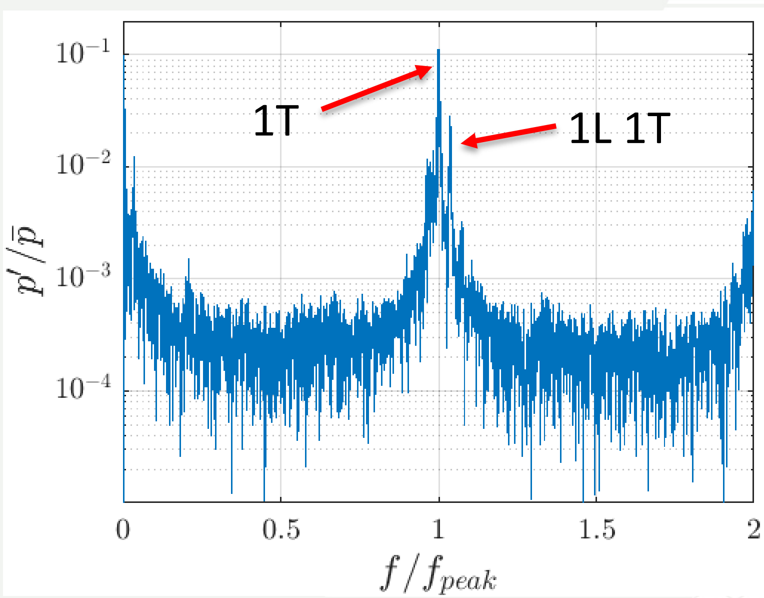
RESEARCH TASK 2

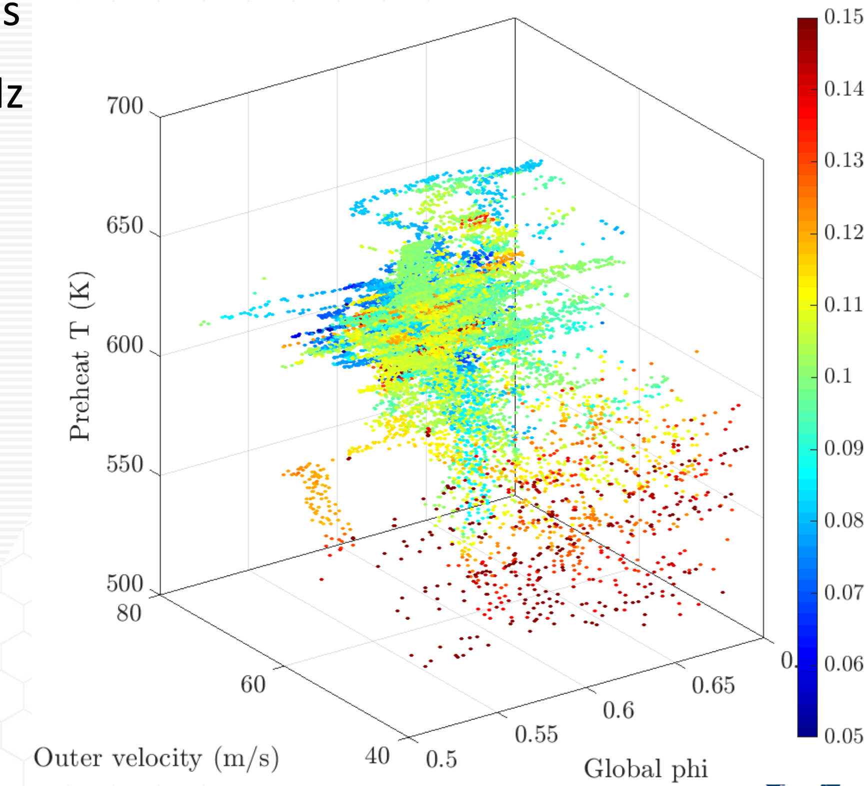
TASK 2.2 - PRESSURE CHARACTERIZATION

- Acquired several hundred operating condition data points

→ Preheat T, global equivalence ratio, pilot ratio ($PR = \frac{\dot{m}_{pilot}}{\dot{m}_{pilot}+\dot{m}_{outer}}$), air mass flow rate.

- Facility exhibits instability for a range of modes
- Today: Focus attention on 1-T mode at 1600 Hz

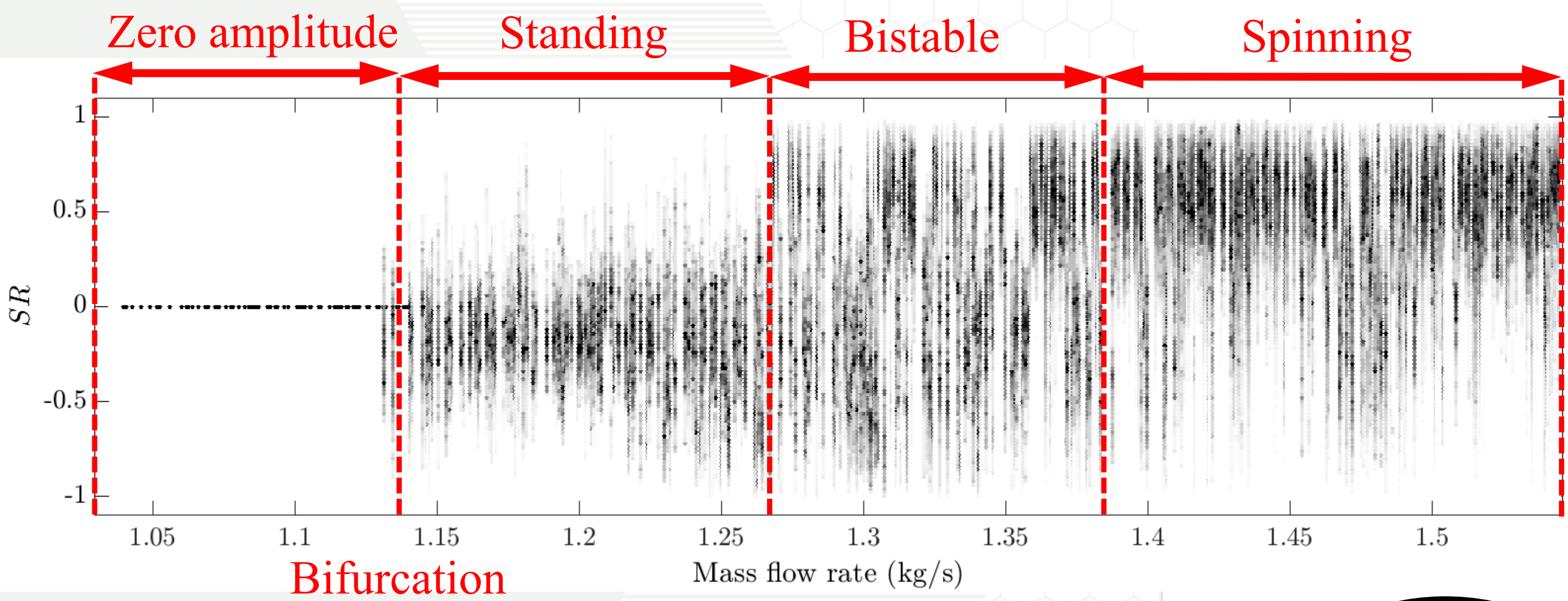




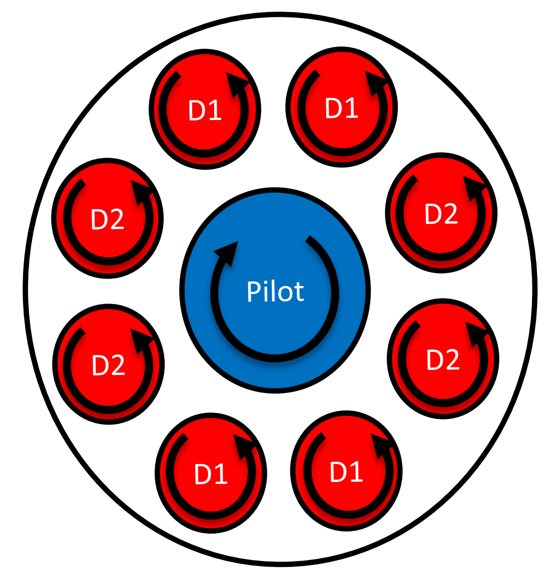
Parameter space

RESEARCH TASK 2

TASK 2.4 MODAL DYNAMICS

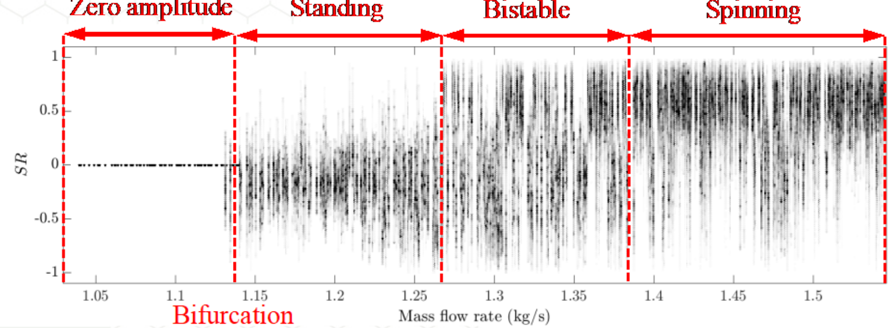


- Spin ratio vs mass flow rate
- Other parameters (preheat temp, pilot ratio, etc) are constant
- Fuel flow rate between D1 and D2 are the same
- Each vertical line is SR histogram at a given mass flow rate



RESEARCH TASK 2

TASK 2.4 MODAL DYNAMICS



Standing mode regime (low flow rate)

- SR: oscillating around zero
- φ_{FG}: oscillating around zero degree

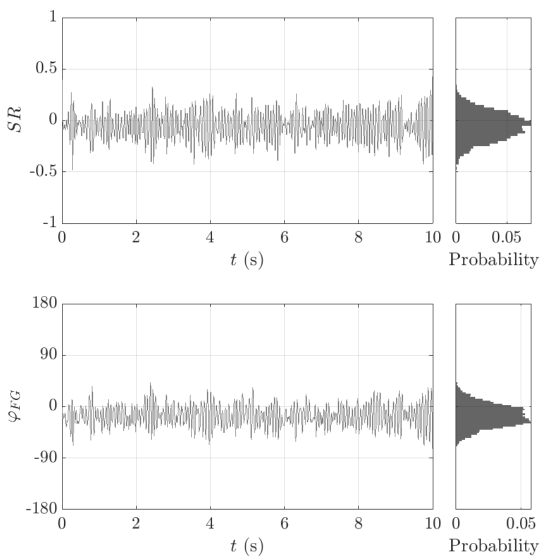
Bistable regime (intermediate flow rate)

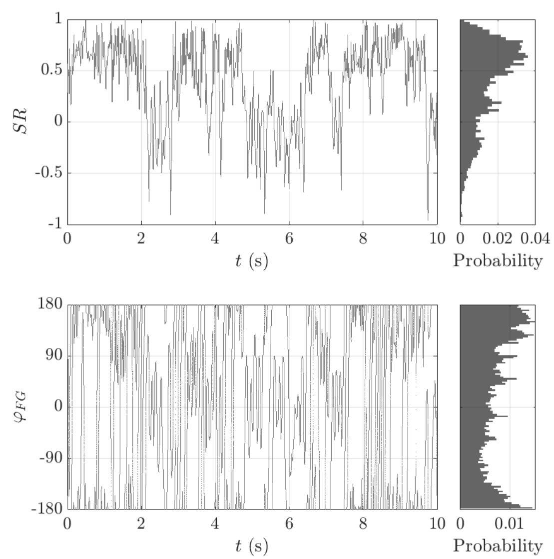
- SR: oscillating between zero and 0.7
- φ_{FG}: oscillating between zero and 180 degree
- System jumps between standing and spinning modes.

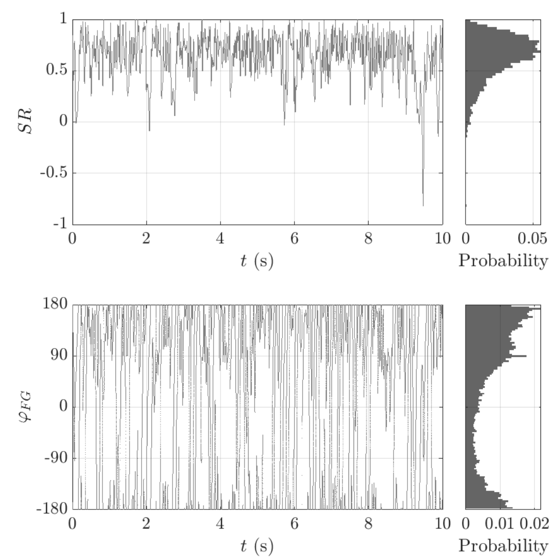
→ Bistable regime

Spinning mode regime (high flow rate)

- SR: oscillating around 0.7
- φ_{FG}: oscillating around 180 degree or drift in one direction







RESEARCH TASK 2

TASK 2.4 MODAL DYNAMICS

Phase portrait in SR and φ_{FG} space

- Gray scale: joint probability of (SR, φ_{FG})
- Red arrow: trajectories
- Head size: magnitude

Standing mode regime

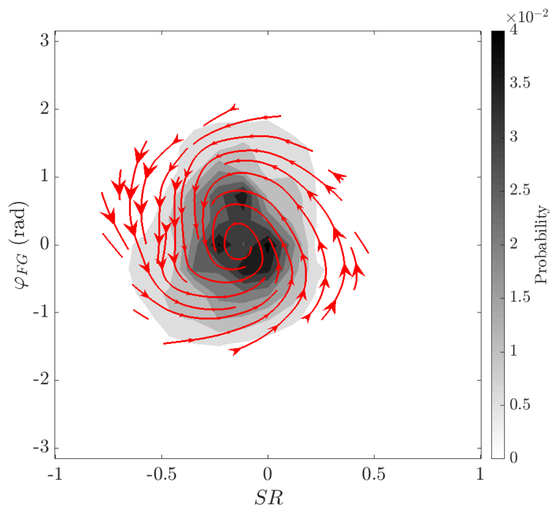
- Single stable attractor appears at the center (standing).
- CCW spiral trajectories around the attractor

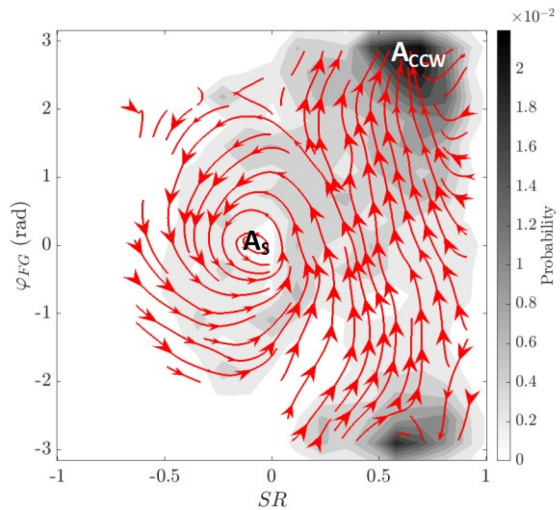
Bistable regime

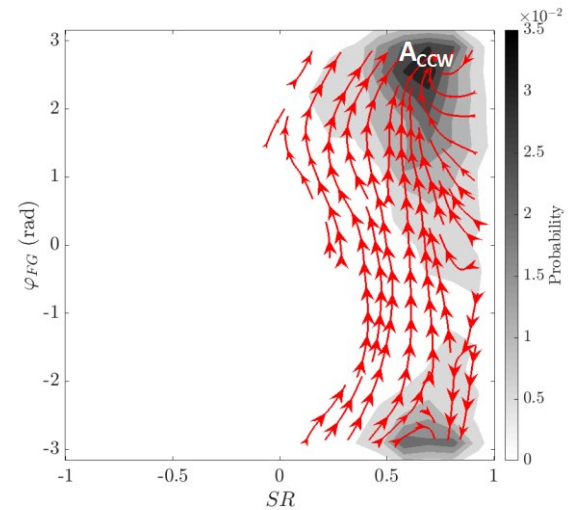
- Two attractors appear, one at the center (standing) and the other at the top right corner (CCW spinning).
- System hops between two stable attractors due to noise effect

Spinning mode regime

- Single stable attractor appears at the top right corner (CCW spinning).
- CCW spiral trajectories around the attractor

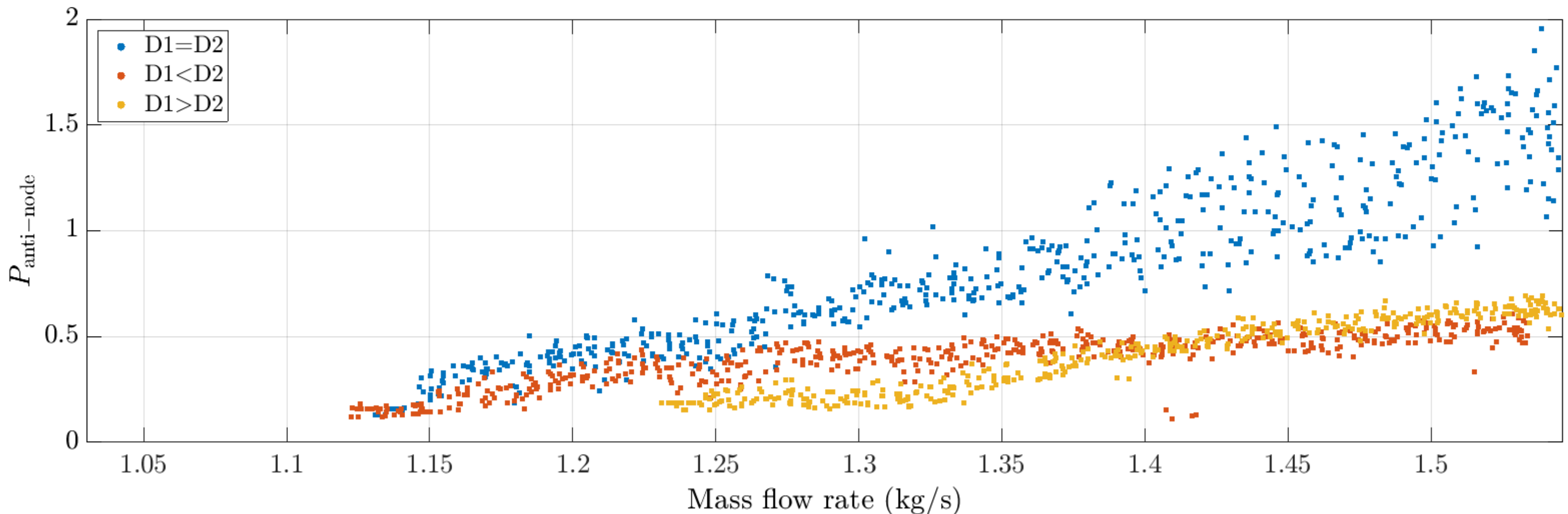


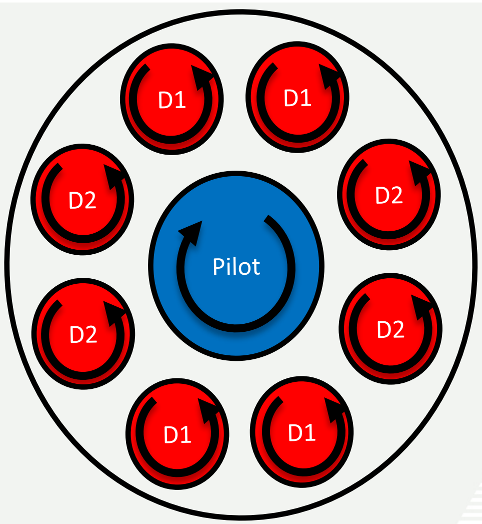




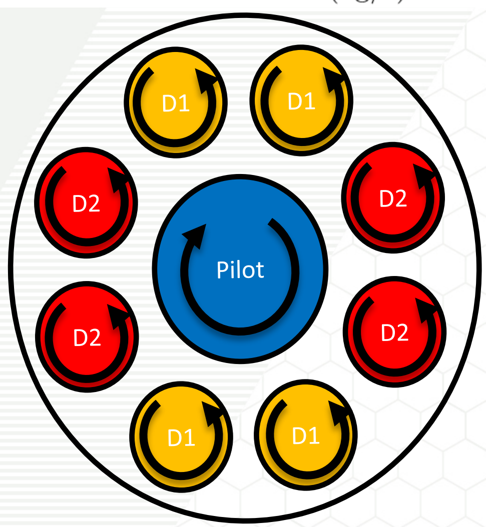
RESEARCH TASK 2

TASK 2.4 MODAL DYNAMICS

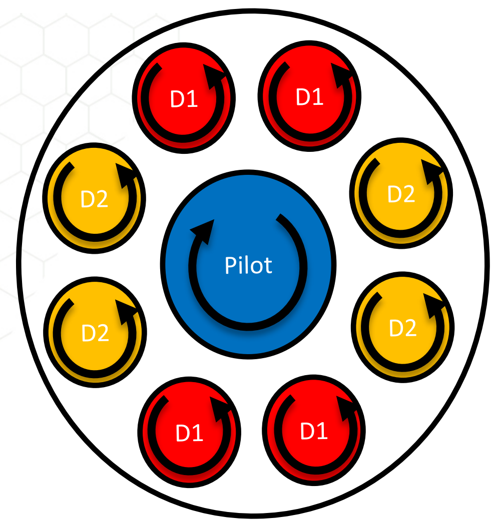




D1=D2



D1<D2



D1>D2

RESEARCH TASK 2

KEY TAKEAWAYS

- ✓ **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**
- ✓ **Observed coherent structure from CH* phase averaged images, suggesting potential mechanism of transverse instability.**
- ✓ **Phase portraits show different types of dominant attractors, leading to substantively different pressure sensor measurements**
- ✓ **Non-uniform azimuthal fuel staging provides a standing mode with anti-node at a fixed location**
- ✓ **Non-uniform azimuthal fuel staging reduces the overall instability amplitude**

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MODELING THE DYNAMICS DURING HIGH-FREQUENCY INSTABILITIES

TASK 3 ACCOMPLISHMENTS

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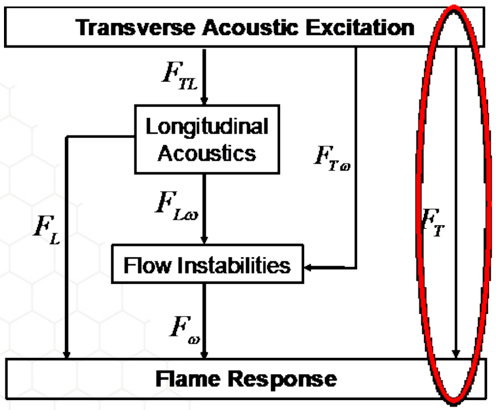
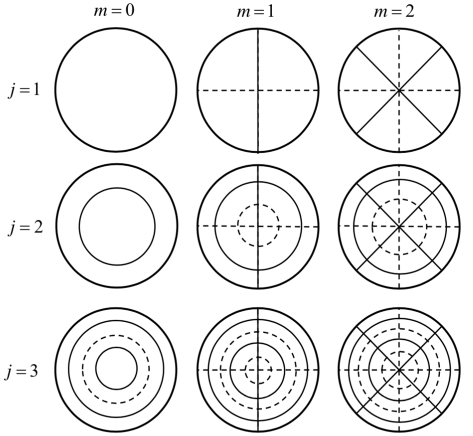
RESEARCH TASK 3.1

VELOCITY COUPLED FLAME RESPONSE

- Focus - Direct excitation by transverse acoustic velocity disturbances F_T

- Modeling Focus
  - For a given flame, how is its stability across different modes?
  - For a given mode, what are the stability boundaries?
  - In a multi-nozzle system, how do different nozzles affect stability?
  - How significant is the transverse excitation response when compared to axial excitation?





Pressure (solid) and velocity (dashed) nodal lines for several lower order transverse modes in a circular duct.

Reproduced from Lieuwen, Unsteady Combustor Physics, 2012

RESEARCH TASK 3.1

METRIC FOR ANALYSIS

High-frequency → Non-compact flames

- Cannot use global heat release dynamics
- Acoustic energy dynamics

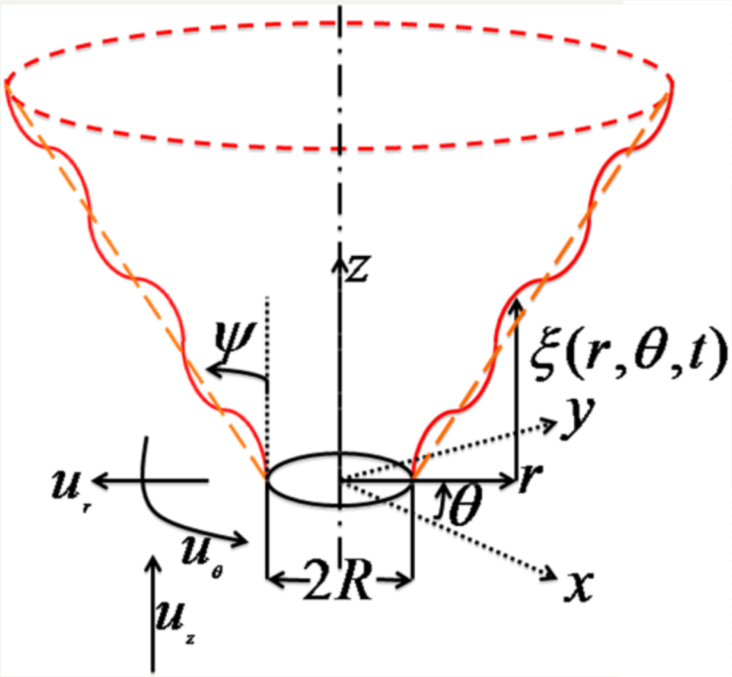
$$\boxed{\frac{\partial}{\partial t}\int_V e_1 dV = \frac{\gamma - 1}{\gamma p_0}\int_V \left(p_1 \dot{q}_1\right) dV - \int_S p_1 \left(\vec{u}_1 \cdot d\vec{S}\right)}$$

A necessary condition for the Rayleigh Integral:

$$\boxed{RI = \int_t \int_V p_1 \dot{q}_1 dV dt > 0}$$

RESEARCH TASK 3.1 PROGRESS

DIRECT EXCITATION MODELING IN THIS DOE PROGRAM



- Explicit flame dynamics

$$\boxed{\frac{\partial \xi}{\partial t} + u_r \frac{\partial \xi}{\partial r} + \frac{u_\theta}{r}\frac{\partial \xi}{\partial \theta} + s_L\left[\left(\frac{\partial \xi}{\partial r}\right)^2 + \frac{1}{r^2}\left(\frac{\partial \xi}{\partial \theta}\right)^2 + 1\right]^{1/2} = u_z}$$

- Normalized Rayleigh Index

$$\boxed{\Re = \frac{RI}{2E}}$$

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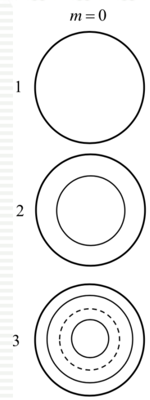
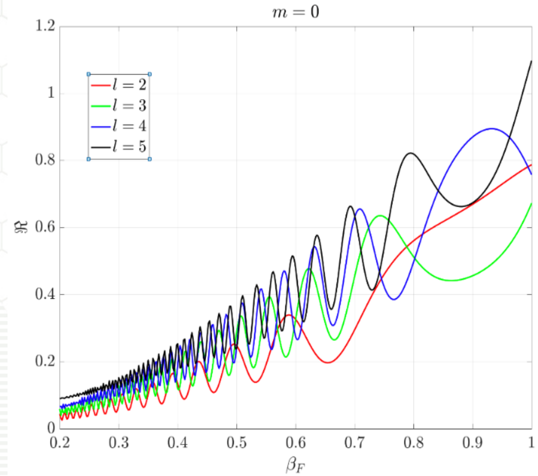
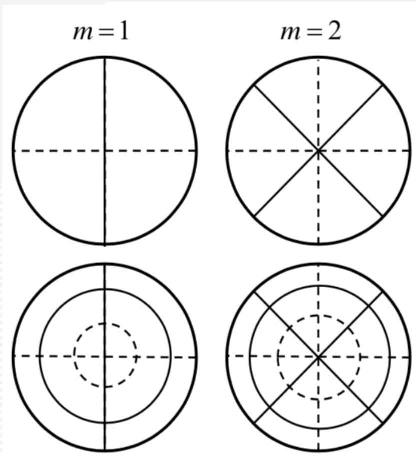
RESEARCH TASK 3.1

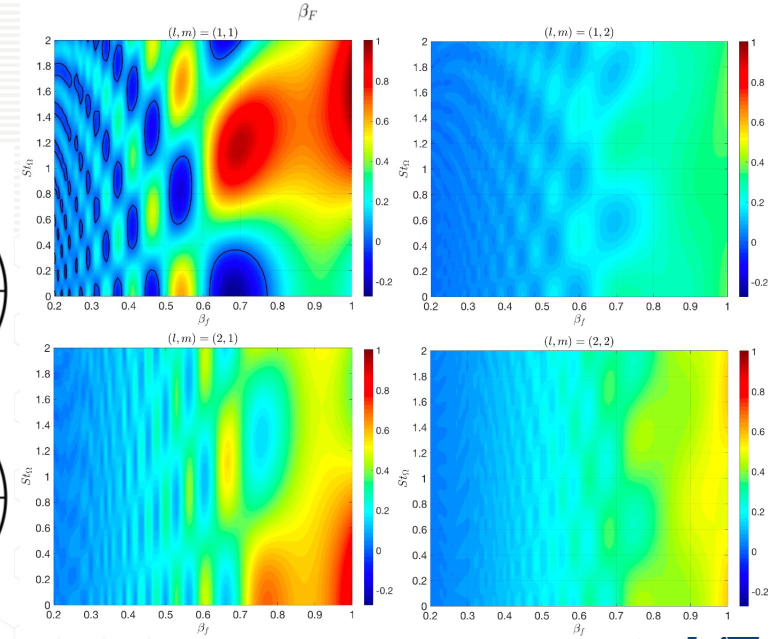
RESULTS – COMBUSTOR CENTERED AXISYMMETRIC FLAME

- Radial modes – always unstable!
- Mixed modes
    - (1,1) mode has islands of stability
    - Other modes are unstable but with lower RI than unstable regions of (1,1) mode





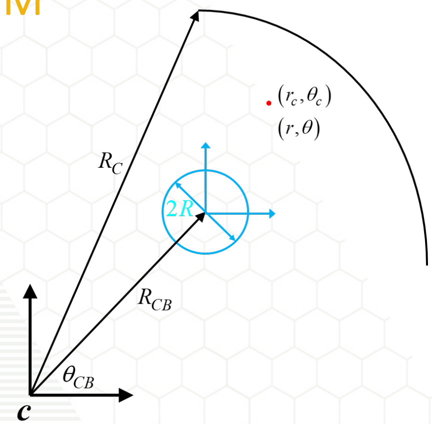




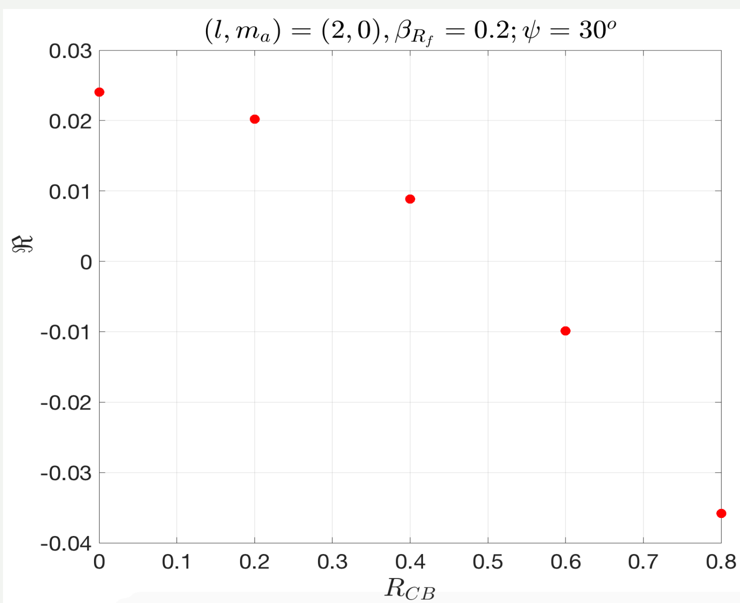
RESEARCH TASK 3.1

RESULTS – STABILITY OF FLAMES OFFSET FROM COMBUSTOR AXIS

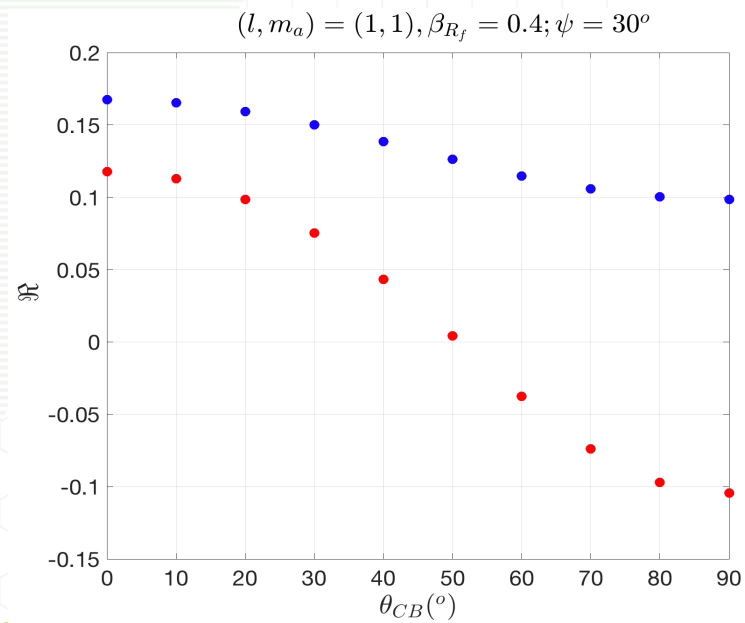
- Flame location relative on mode shape affects RI
  - Nozzle offset from axis implies, local azimuthal acoustic velocity affects RI



Outward radial offset increases stability



Azimuthal offset increases stability



RESEARCH TASK 3.1

RESULTS – MEAN FLAME ASYMMETRY EFFECTS

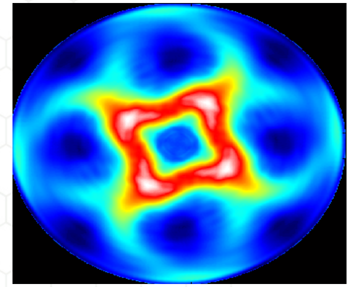
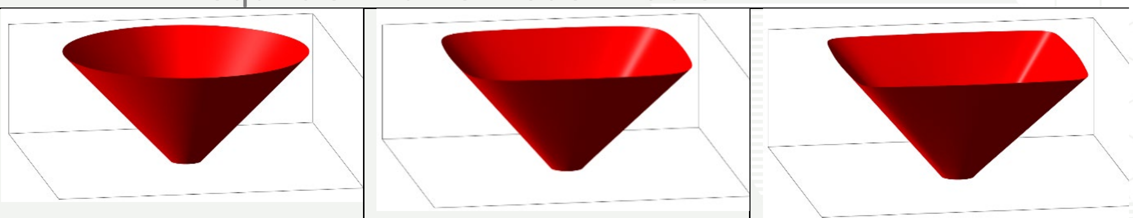


Image courtesy – Samarasinghe & Santavicca

- Multi-nozzle flame-flame interactions
  - "Squircle" Flame Model Problem

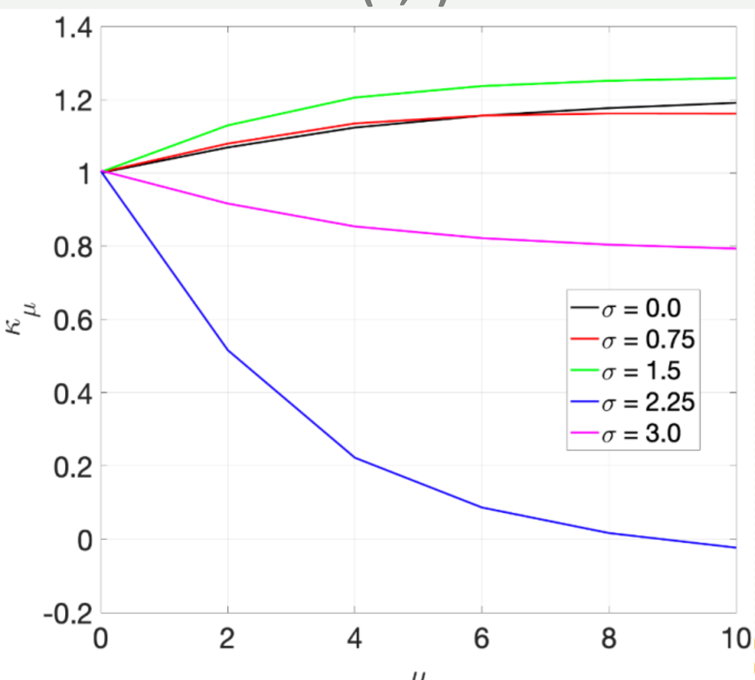


(a) $\mu = 0$ **(b)** $\mu = 4$ **(c)** $\mu = 10$

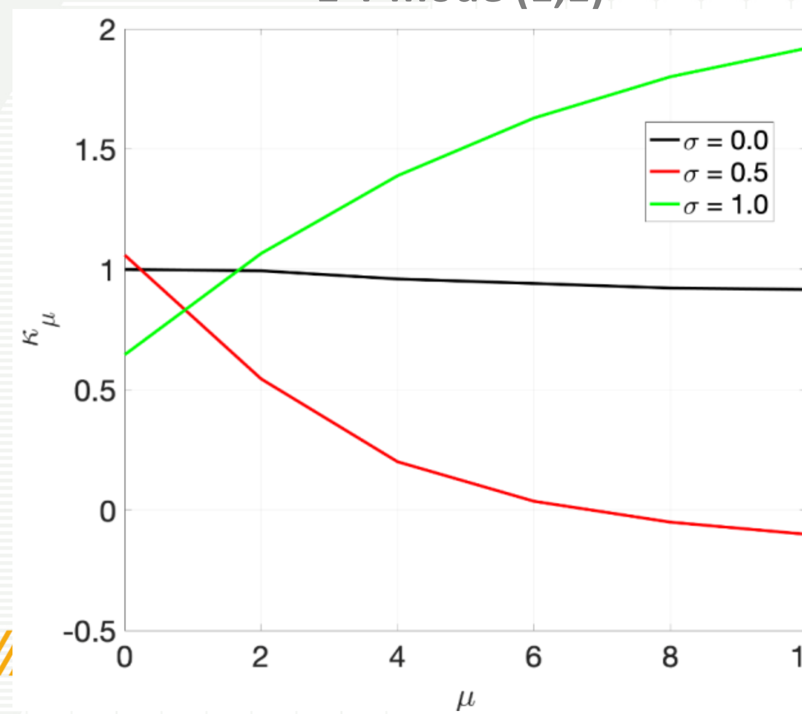
- Define a quantity to characterize effect of asymmetries:

$$\kappa_\mu = \frac{\Re_\mu}{\Re_{\mu=0}(\sigma = 0)}$$

Radial mode (2,0)



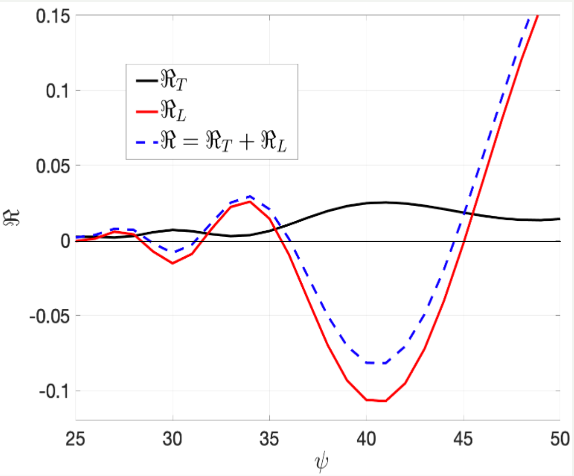
1-T mode (1,1)



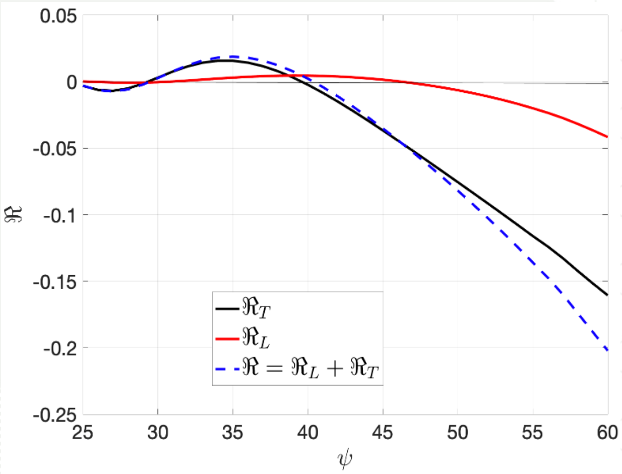
RESEARCH TASK 3.1
INDUCED AXIAL FLUCTUATIONS

- Prior results focus purely on direct excitation from transverse acoustics
  - Transverse acoustics induce axial velocity fluctuations at the nozzle
  - Induced axial fluctuations related to pressure field at nozzle → Nozzle location in transverse acoustic mode is important
  - Focus: Compare growth rate due to direct excitation with corresponding induced axial excitation for relative significance.

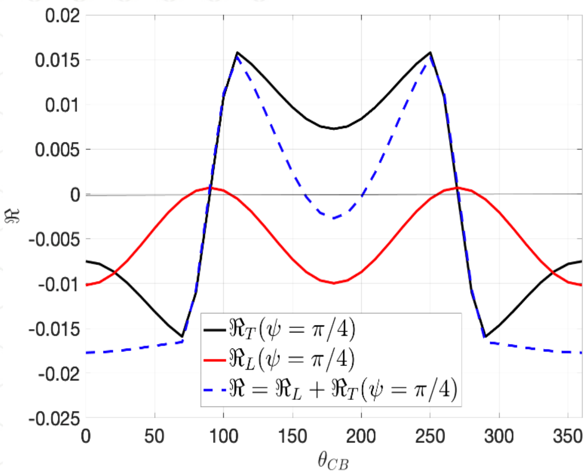
$(2,0)$



$(1,1)$



Azimuthal offset: $(1,1)$



RESEARCH TASK 3.1 SUMMARY

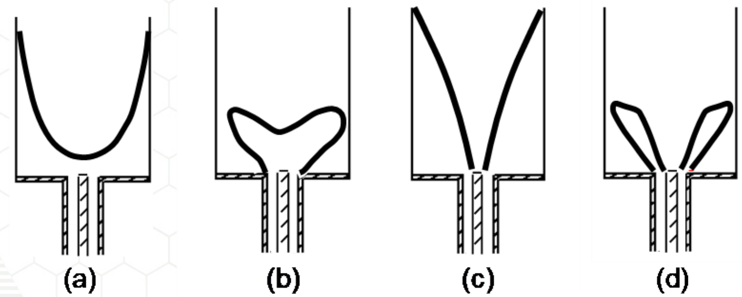
- Stability for low-frequency compact flames: global flame transfer function
- Stability for high frequency non-compact flames: Rayleigh index
- Modeling studies
  - Axisymmetric mean flames centered in combustor
  - Axisymmetric mean flames offset from combustor axis
  - Non-axisymmetric mean flame effects
  - Comparison to induced axial excitation
- Varying degrees of positive/negative amplification of normalized Rayleigh index depending on mode, flame location, flame shape and flow parameters.
- Modeling the mode amplification factor may require the inclusion of the induced axial mechanism along with the direct excitation mechanism.

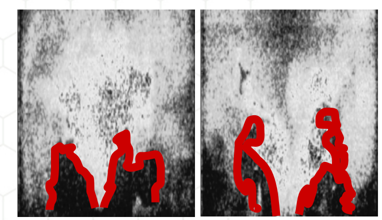
RESEARCH TASK 3.2

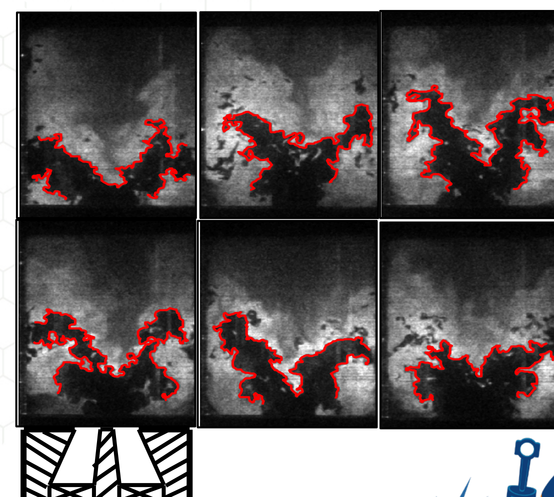
HYDRODYNAMIC STABILITY MODELING

- 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.



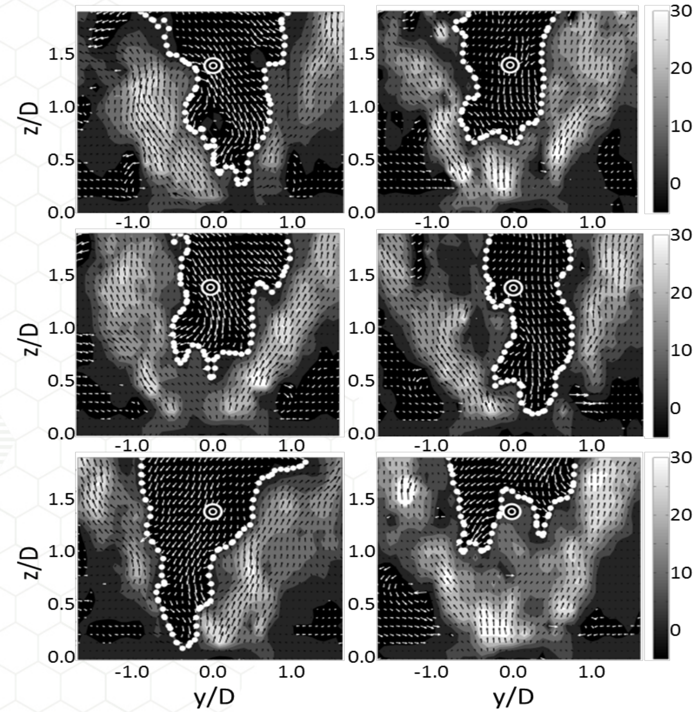




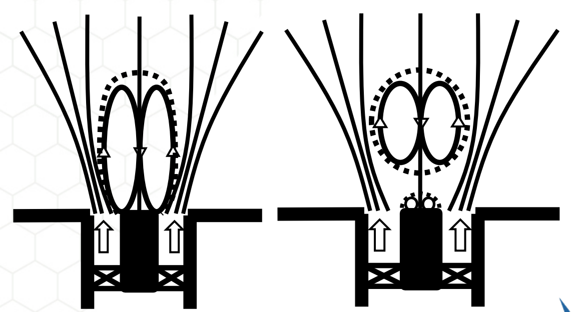
RESEARCH TASK 3.2

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



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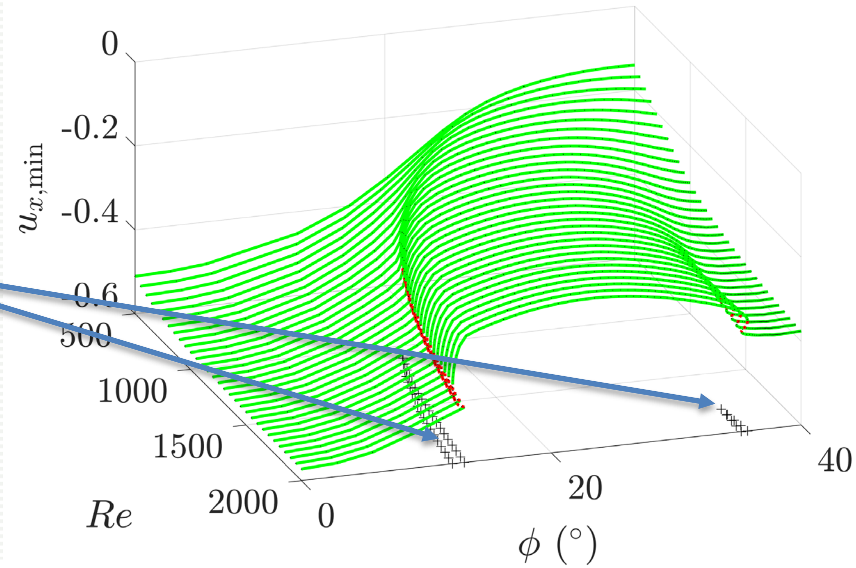
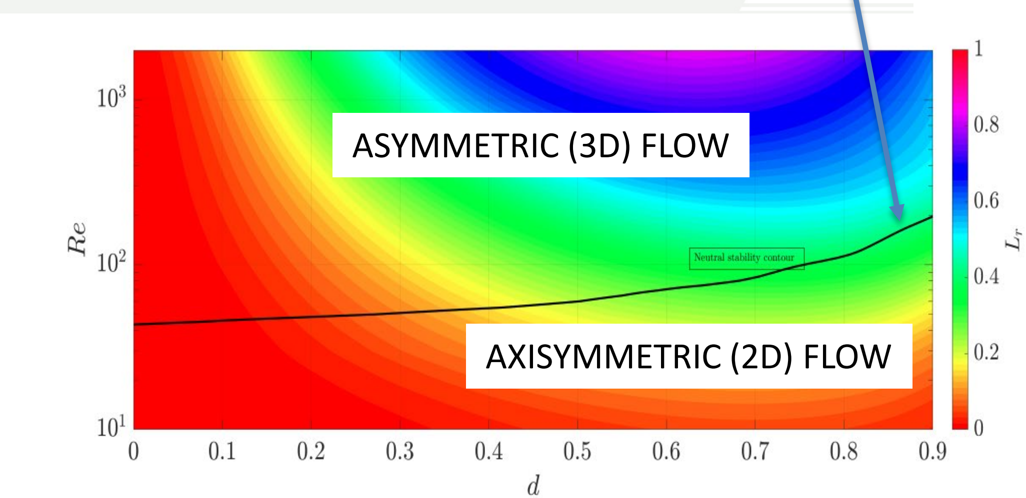
RESEARCH TASK 3.2

HYDRODYNAMIC STABILITY MODELING

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





<u>When are certain families of solutions possible?</u>

RESEARCH TASK 3.2

HYDRODYNAMIC STABILITY MODELING

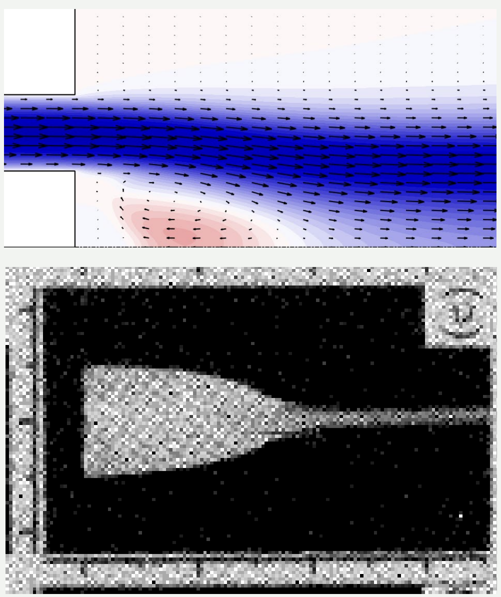
Georgia Tech

Nature of centerbody wake/vortex breakdown changes with geometry, swirl number, and Reynolds number

BASE FLOW

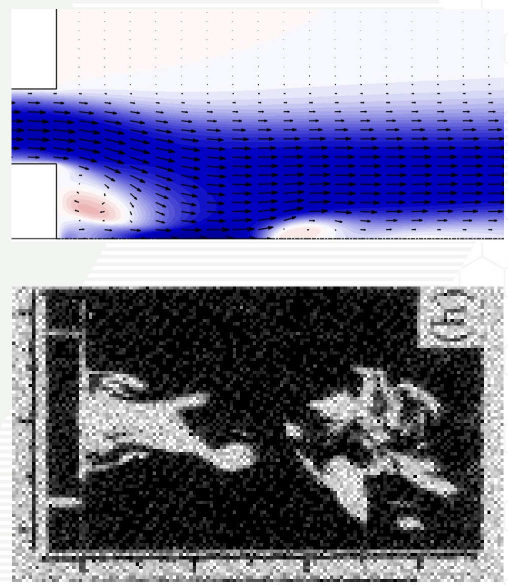
EXPERIMENT

Recirculation zone with vortex tube

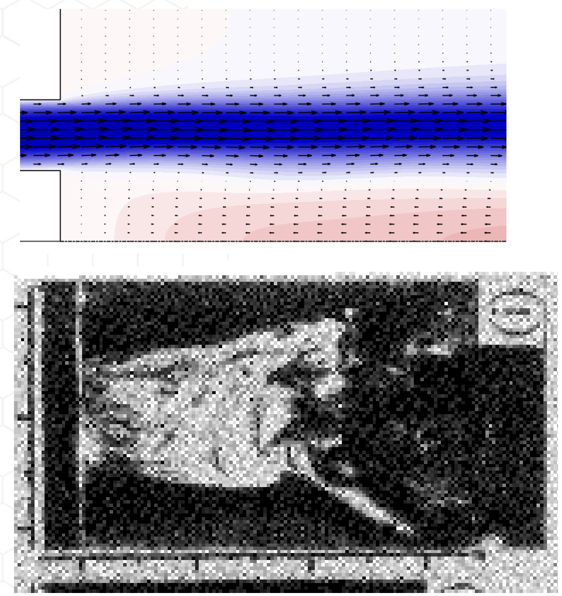


Sheen *et al.*, Phys. Fluids, 1996

Recirculation zone with bubble-like breakdown above



Merged recirculation zones



Swirl number

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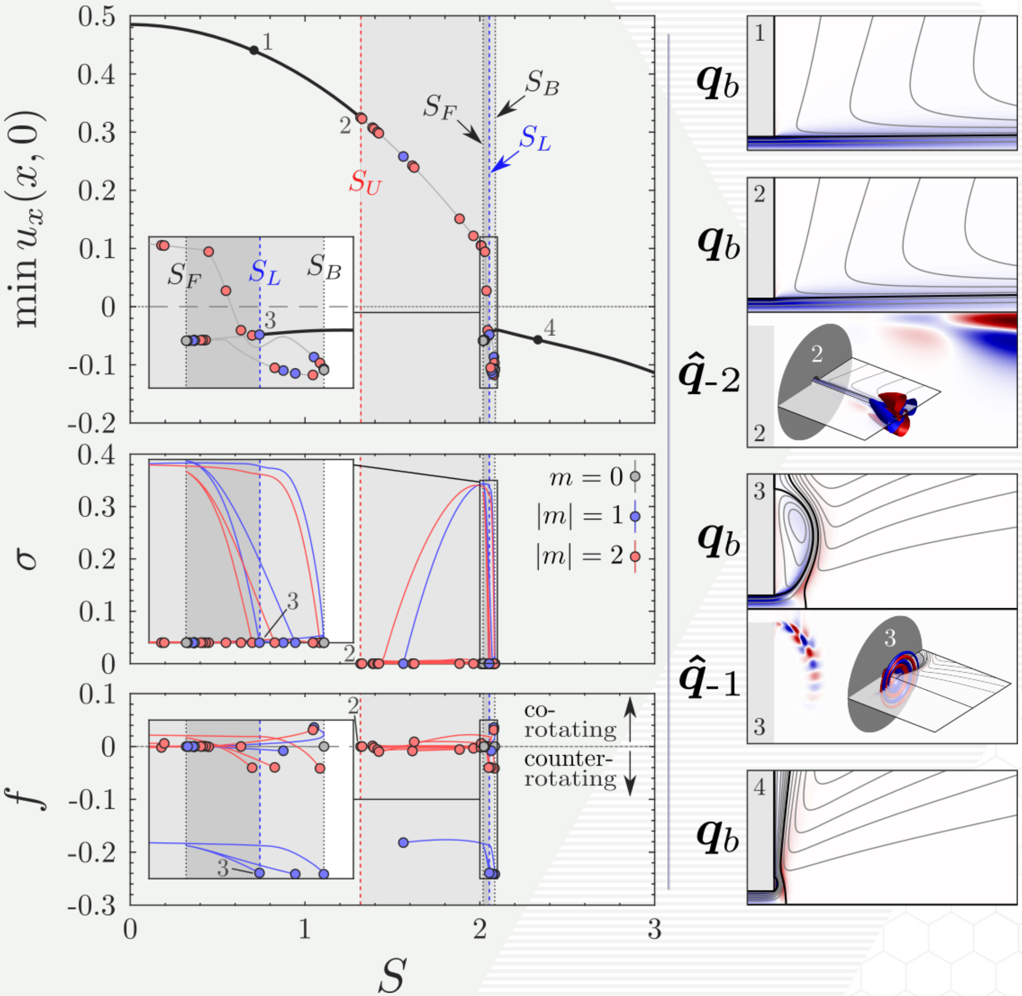
Dynamics of a circular jet (no centerbody)



Complicated sequence of Hopf and saddle-node bifurcations leads to strongly nonlinear dynamics even at low Re.

Even without instability, the evolution of vortex breakdown in the steady "base" flow is quite complicated, exhibiting hysteresis with changing swirl.

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RESEARCH TASK 3.2

HYDRODYNAMIC STABILITY MODELING

Examples of <u>nonlinear</u> (not eigenmodes!) limit cycle oscillations in laminar swirling circular jets

$|m|=1$

$|m|=2$

RESEARCH TASK 3.2

TAKEAWAYS

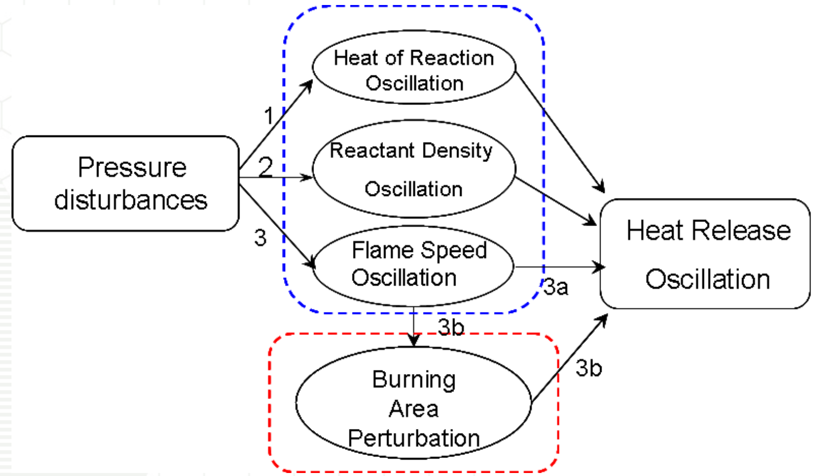
- Flame shape and stabilization cannot be predicted reliably without excellent understanding of underlying fluid mechanics.

- Swirling flows exhibit strong hysteresis and three-dimensionality, influencing both flame position and nature of flow disturbances exciting the flame

RESEARCH TASK 3.3

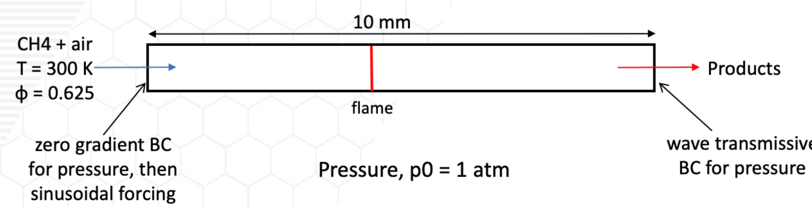
PRESSURE COUPLING MECHANISM FOR HIGH FREQUENCY INSTABILITIES

- Study direct effect of pressure fluctuations on local heat release rate oscillations
  - Generalize prior single-step approach using large kinetic mechanisms
- 1D laminar flame using a Low Mach solver with thermodynamic pressure modulation



$$\frac{\partial \rho c_p T}{\partial t} + \nabla \cdot (\rho \mathbf{u} h) - \frac{dp_t}{dt} = \nabla^2(\alpha \rho c_p T) + \dot{R}_h$$

$$p_t(t) = p_0 + p_a(t) = p_0 + A_p sin(\omega t)$$



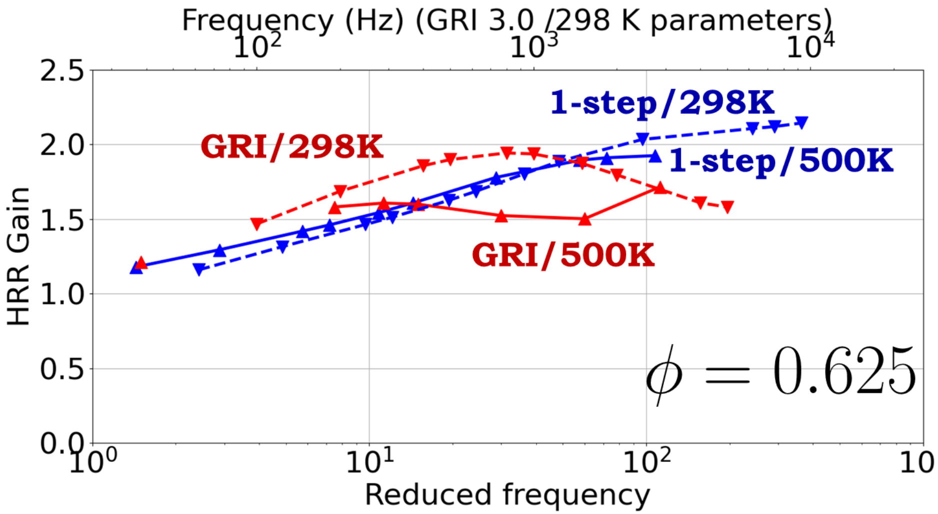
- Define reduced frequency: $\omega = 2\pi f \tau_F$

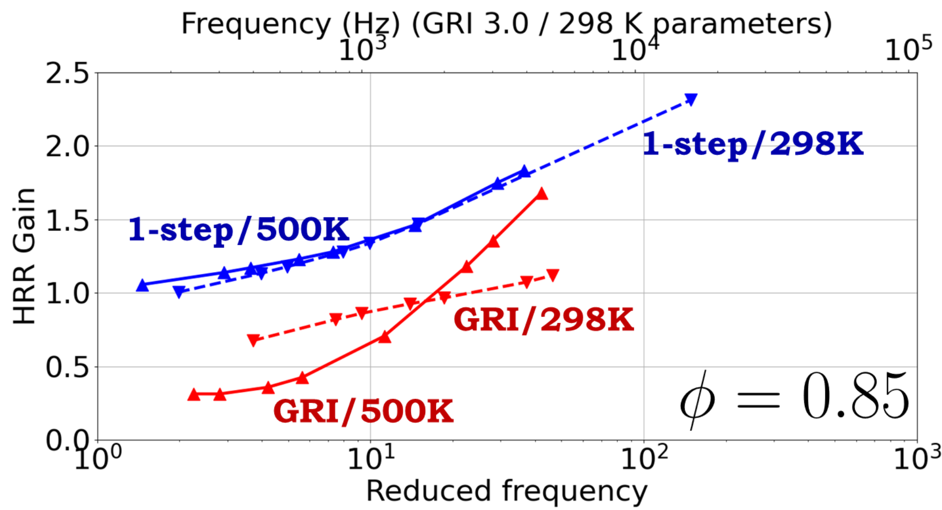
$$l_{F_0} = \frac{T_b - T_u}{\max \frac{dT}{dx}} \qquad \tau_F = \frac{l_{F_0}}{s_{L_0}}$$

RESEARCH TASK 3.3

PRESSURE COUPLING MECHANISM FOR HIGH FREQUENCY INSTABILITIES

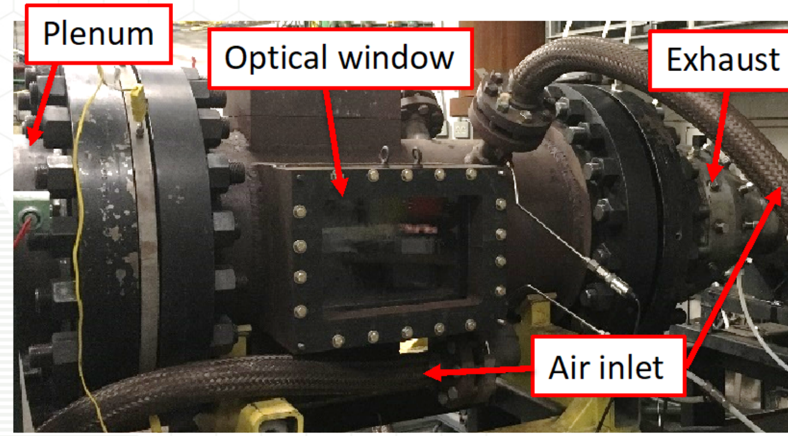
- Kinetic Mechanisms for CH4/air
  - 1-step (1S) from Cerfacs (5 species)
  - GRI Mech 3.0 (53 species, 325 reactions)
- Characterize response using transfer function defined as: $$G_{\dot{Q}} = \frac{A_{\dot{Q}}}{\bar{\dot{Q}}} \frac{p_0}{A_p}$$
- Vary reduced frequency for fixed pre-heating and equivalence ratio

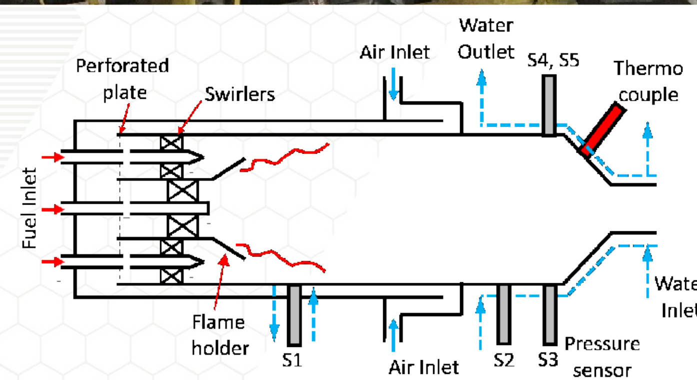




KEY ACCOMPLISHMENTS FROM EXPERIMENTS

- ✓ 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





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KEY ACCOMPLISHMENTS FROM MODELING

- ✓ Flame response modeling framework for 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
- ✓ Hydrodynamic stability modeling
  - Internal tool developed to study hydrodynamic stability in reacting flows using FreeFEM++
  - Modeling of swirling flow instabilities
- ✓ Pressure coupling mechanism
  - Effects of pressure fluctuations on flame response through reacting 1D simulations