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

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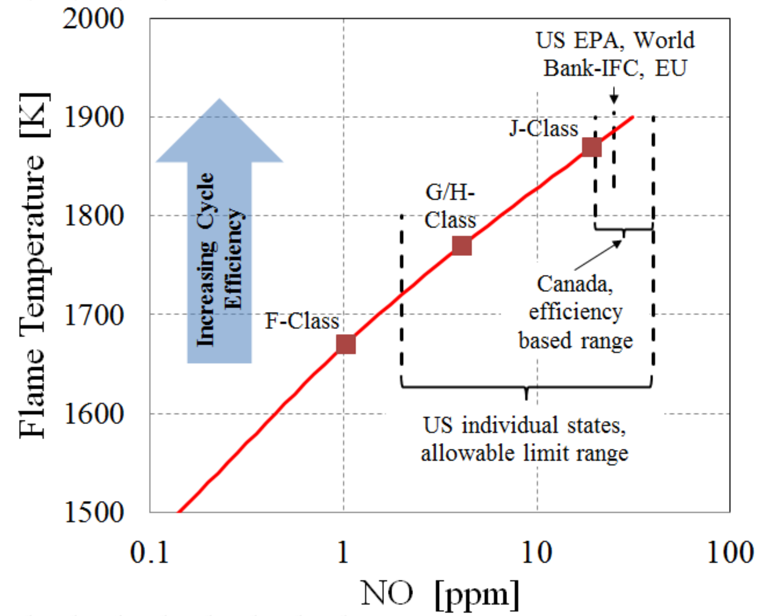
MOTIVATION FOR RESEARCH

- 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

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

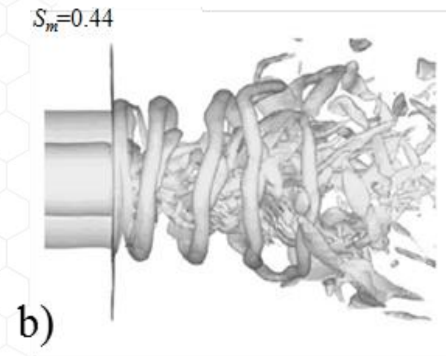


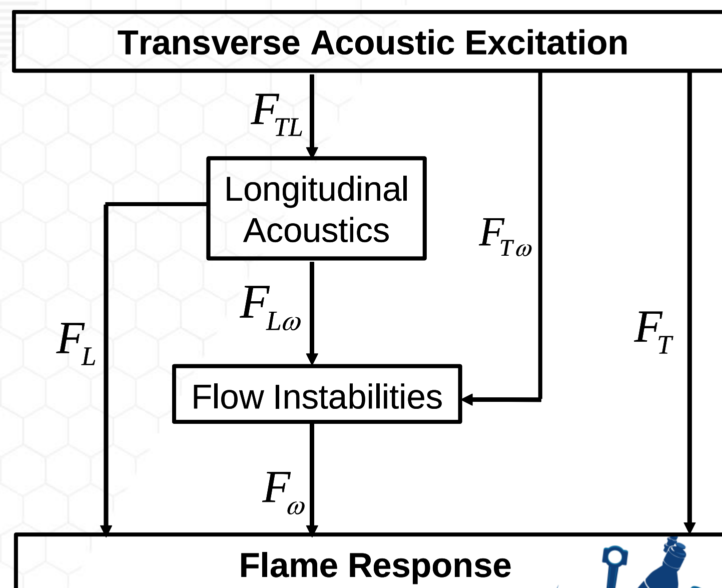
Realistic multi-nozzle experiments and high frequency modeling capabilities needed

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.

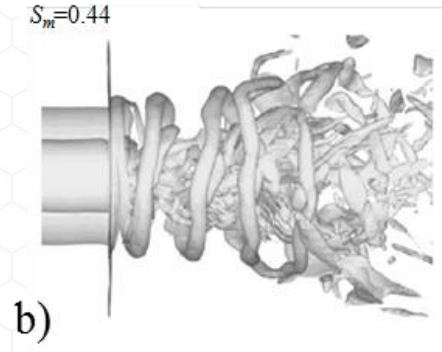


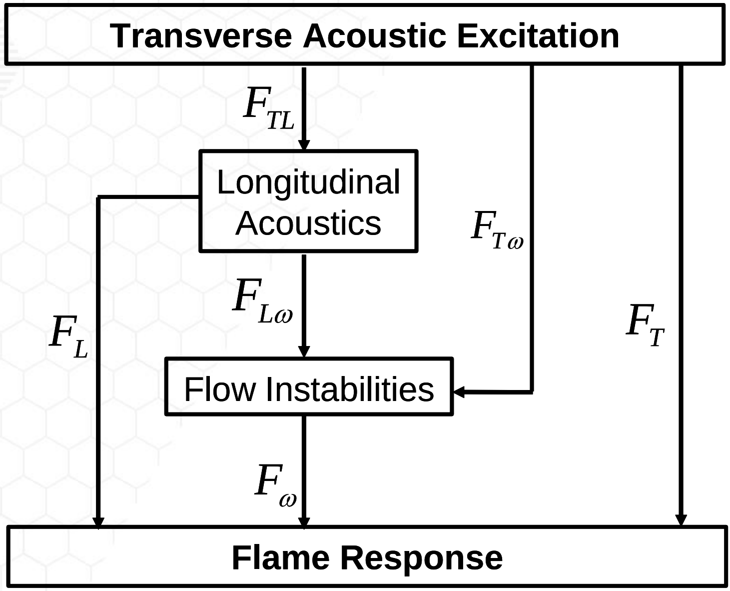


DISTINGUISHING FEATURES OF HIGH FREQUENCY, TRANSVERSE INSTABILITIES

- Acoustic 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

- Coupling mechanisms
  - Velocity
  - Equivalence ratio
  - Direct kinetic (pressure) coupling?
    - Negligible at “low frequencies”





RESEARCH FOCUS

- <u>**Key research questions**</u>:

(1) How do the conventional coupling mechanisms from low-frequency translate to high-frequency?

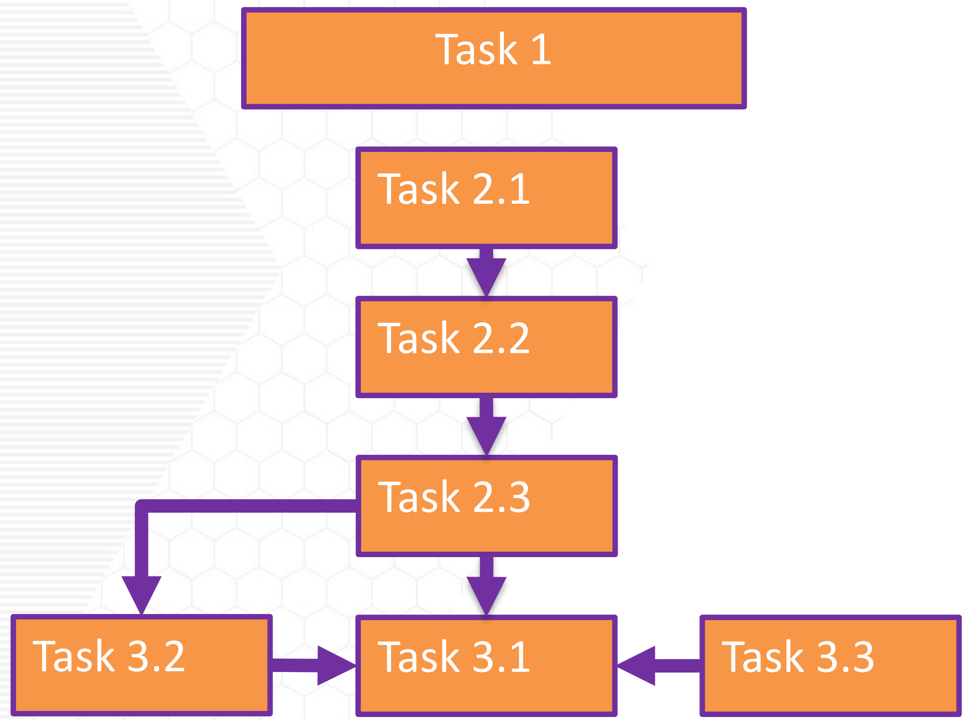
(2) How do coherent structures interact with high-frequency acoustic forcing?

(3) What are the new mechanisms that are of importance at high frequencies and what are their relative roles when compared to the conventional mechanisms?

(4) How does the direct effect of pressure fluctuations influence the thermoacoustic stability of the system?

TASKS & CONNECTIONS

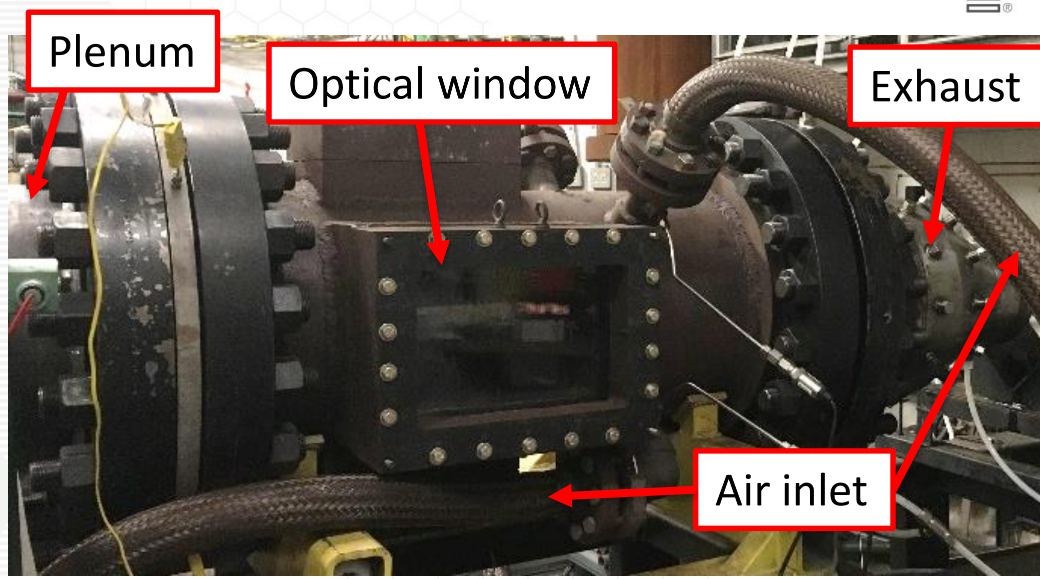
- Task 1: PMP
- Task 2: Experiments on self-excited transverse instabilities
  - 2.1 – Design of Experiment
  - 2.2 – Pressure characterization
  - 2.3 – Flow and flame characterization
- Task 3: Reduced order modeling for thermoacoustic coupling
  - 3.1 – Flame response modeling
  - 3.2 – Hydrodynamic stability modeling
  - 3.3 – Kinetic coupling mechanism modeling

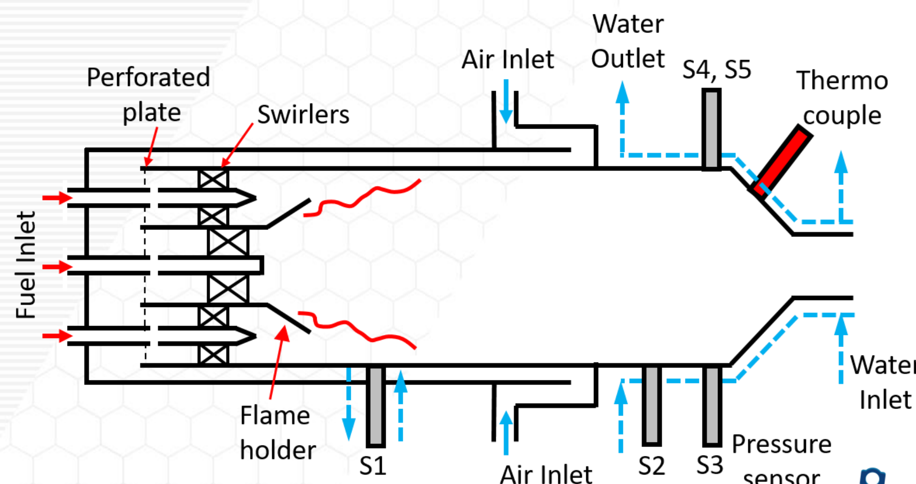


RESEARCH TASK 2

TASK 2.1 PROGRESS (EXPERIMENTAL COMBUSTOR)

- 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.





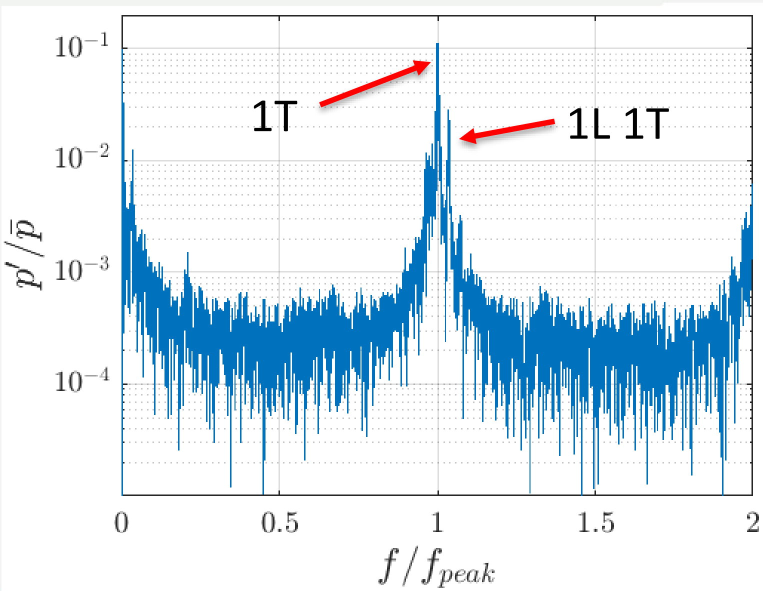
RESEARCH TASK 2

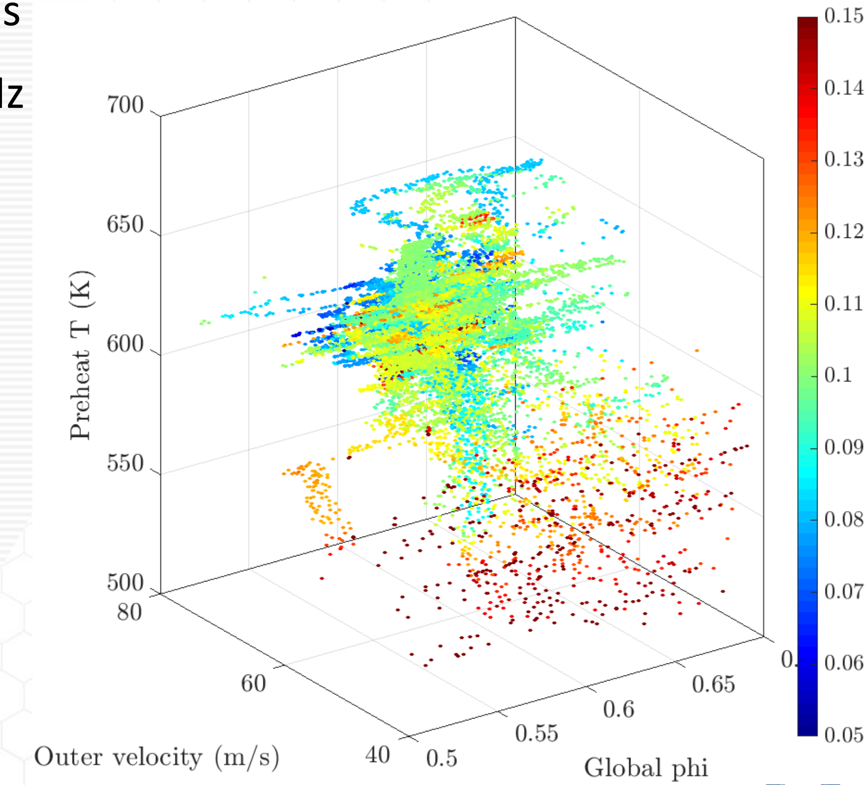
TASK 2.2 PROGRESS (PRESSURE CHARACTERIZATION)

- 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

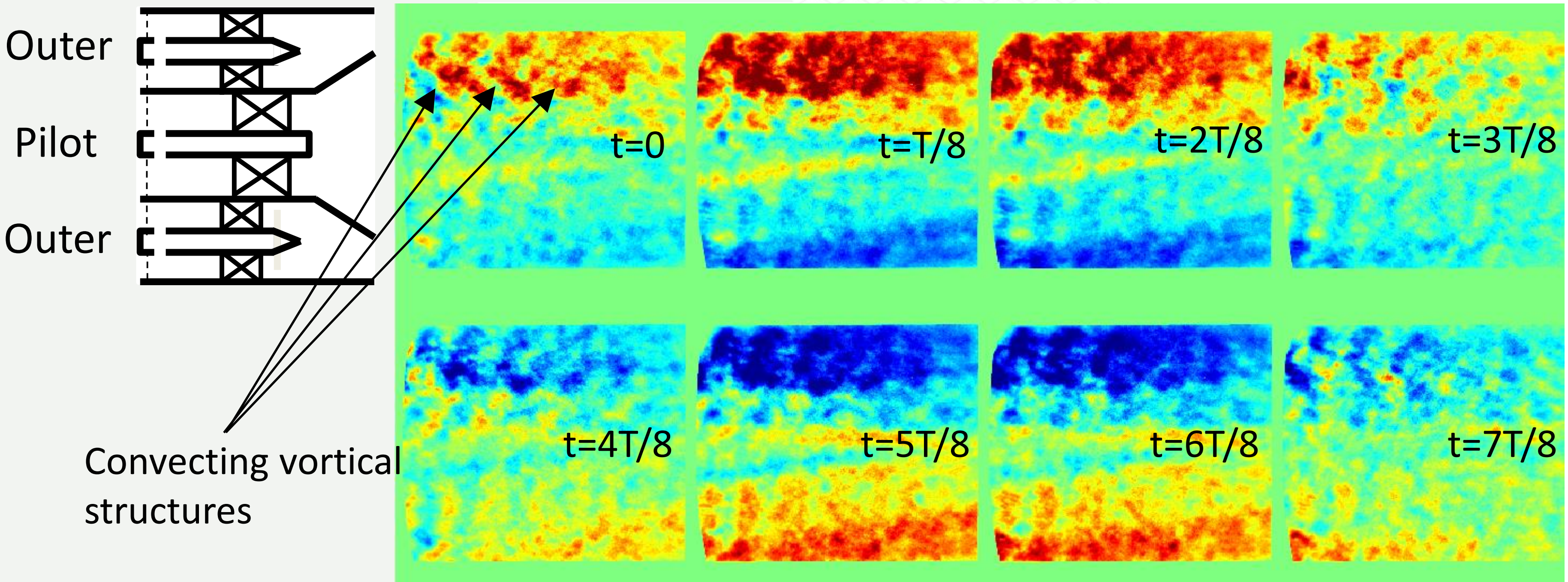




Parameter space

RESEARCH TASK 2

TASK 2.3 PROGRESS (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 PROGRESS (PRESSURE CHARACTERIZATION)

- Pressure decomposition

$$\hat{p}(\theta,t) = \underbrace{F(t)e^{i(\theta+\psi_F-\omega_F t)}}_{CCW} + \underbrace{G(t)e^{-i(\theta-\psi_G+\omega_G t)}}_{CW}$$

- Given multiple signals,

$$\underbrace{\begin{bmatrix} \hat{p}(\theta_1,t) \\ \hat{p}(\theta_2,t) \\ \vdots \\ \hat{p}(\theta_n,t) \end{bmatrix}}_{=P(measure)} = \underbrace{\begin{bmatrix} e^{i\theta_1} & e^{-i\theta_1} \\ e^{i\theta_2} & e^{-i\theta_2} \\ \vdots & \vdots \\ e^{i\theta_n} & e^{i\theta_n} \end{bmatrix}}_{=M(known)} \underbrace{\begin{bmatrix} Fe^{i(\psi_F-\omega_F t)} \\ Ge^{i(\psi_G-\omega_G t)} \end{bmatrix}}_{=X(unknown)} \rightarrow P = M \cdot X$$

- Least squares fit

$$X = (M^T M)^{-1} M^T P = \begin{bmatrix} Fe^{i(\psi_F-\omega_F t)} \\ Ge^{i(\psi_G-\omega_G t)} \end{bmatrix}$$

RESEARCH TASK 2

TASK 2.2 EXTRACTED PARAMETERS

- Magnitude of each wave (CW and CCW) and spin ratio (SR):

$$|X| = \begin{bmatrix} |F| \\ |G| \end{bmatrix} \rightarrow SR = \frac{|F| - |G|}{|F| + |G|} \quad where \begin{cases} SR = 0: standing\ mode \\ SR = \pm 1: CCW/CW\ spinning\ mode \\ o.w: mixed\ mode \end{cases}$$

- Phase difference between CW and CCW waves, ϕ:

- Anti-nodal line, θ_a (location where pressure mag. is maximum):

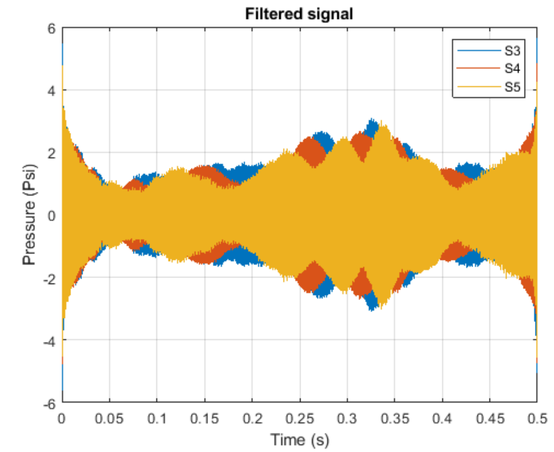
- Anti-nodal line velocity, $\Omega_a = \frac{d\theta_a}{dt}$

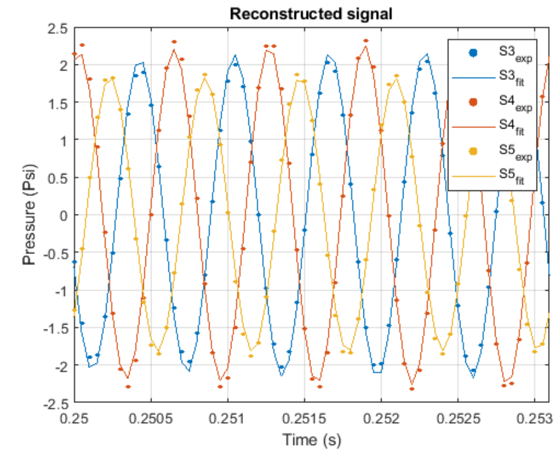
- Total pressure magnitude: $(2F^2 + 2G^2)^{1/2}$

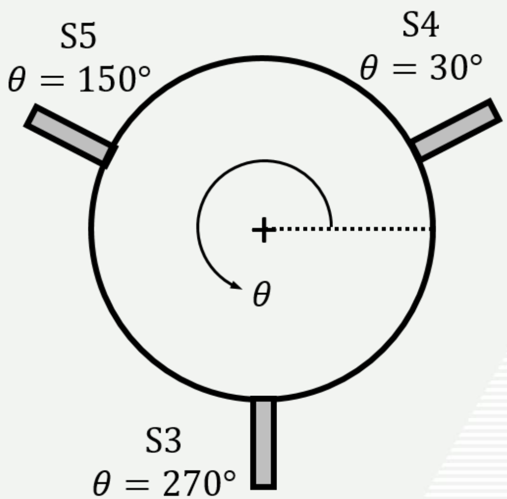
RESEARCH TASK 2

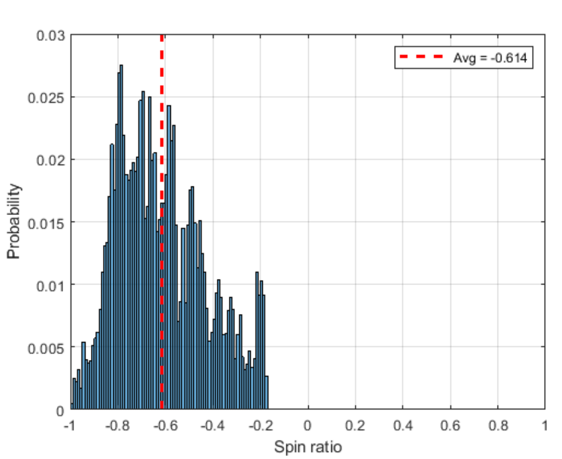
TASK 2.2 EXAMPLE- EXTRACTED PARAMETERS

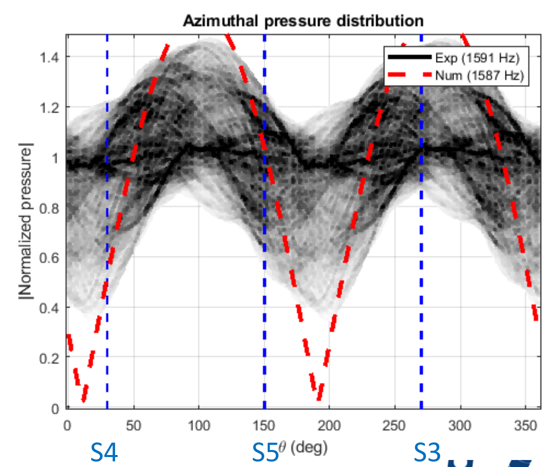
Identification of acoustic mode shape- Azimuthal dependency





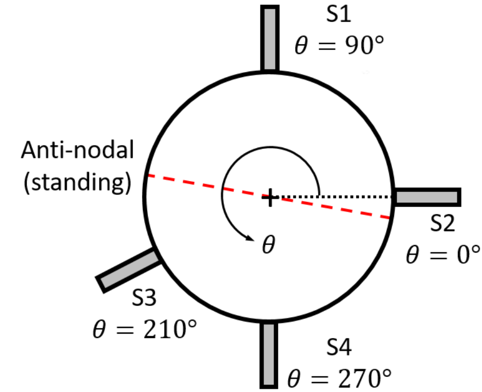




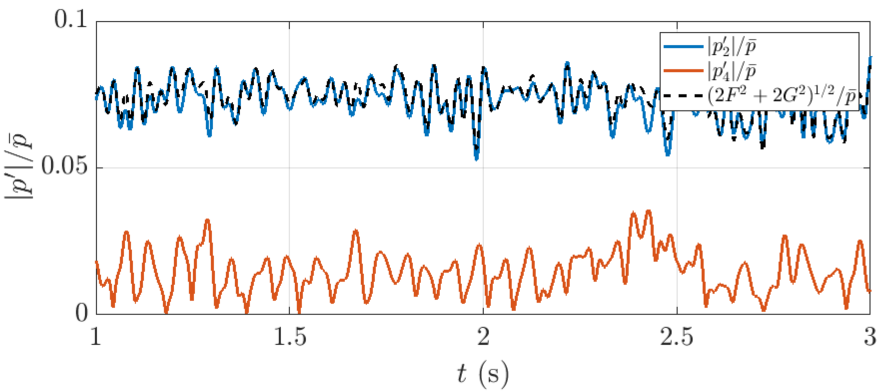


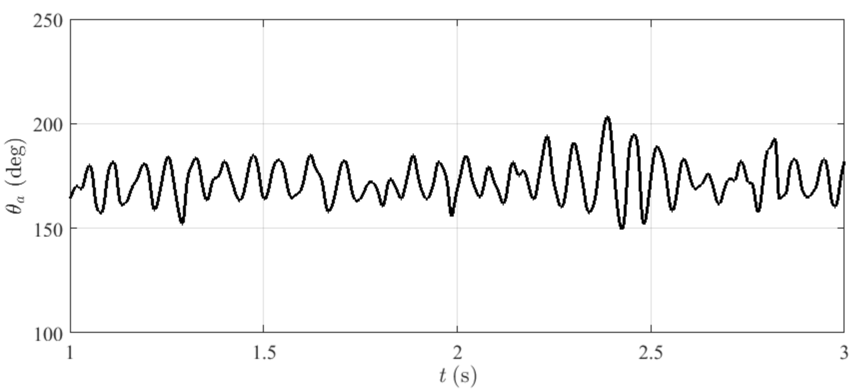
RESEARCH TASK 2

TASK 2.2 MODAL DYNAMICS

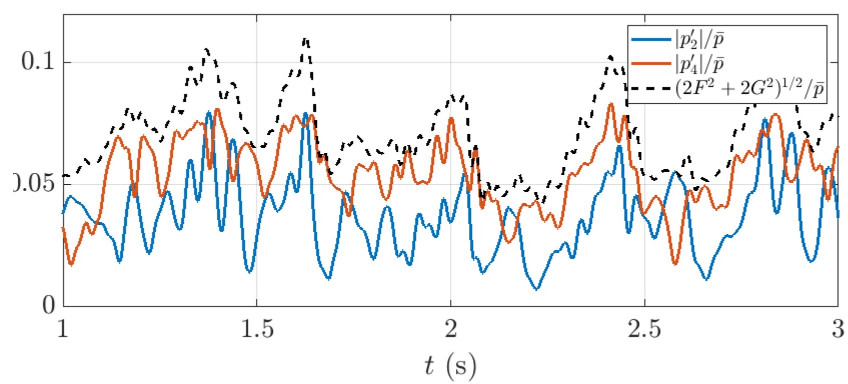


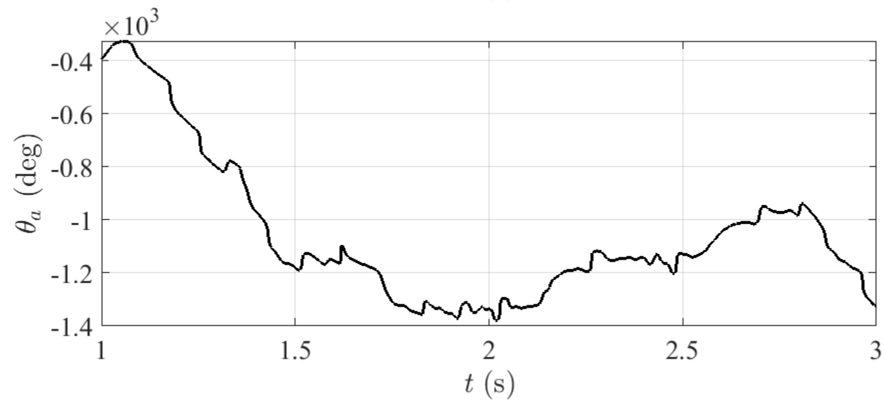
Case 1 (standing dominant)





Case 2 (CW dominant)



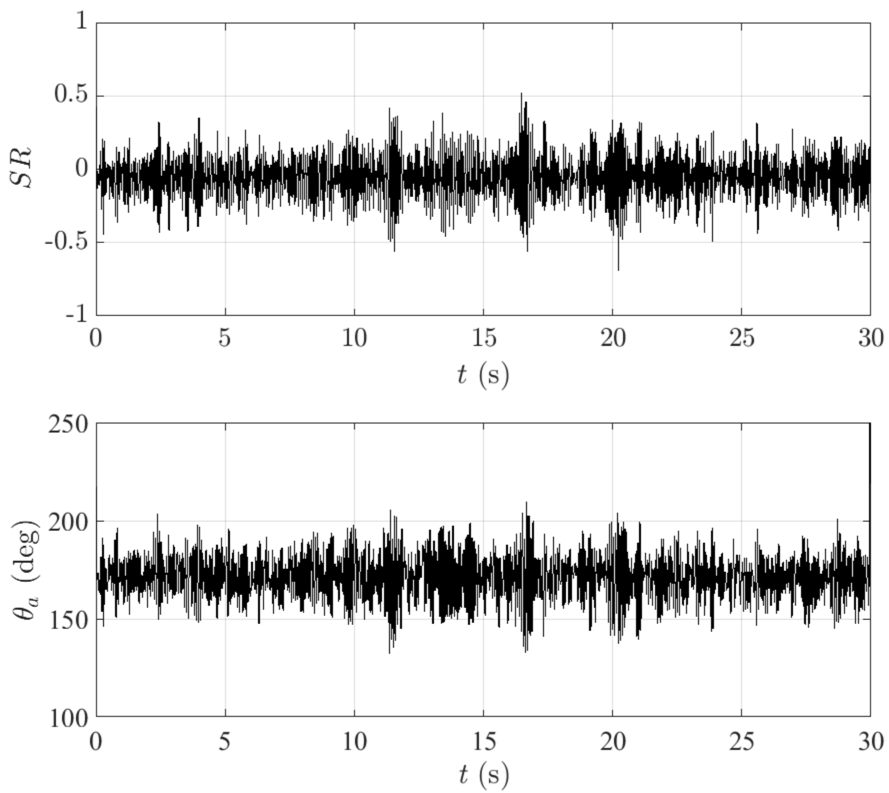


RESEARCH TASK 2

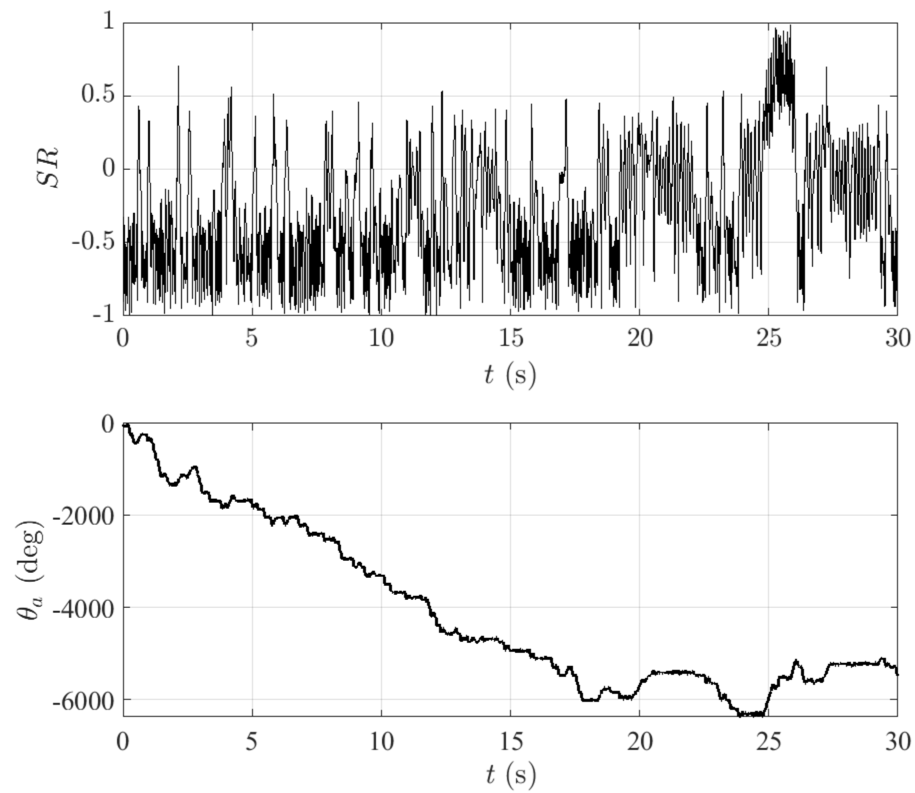
TASK 2.2 MODAL DYNAMICS

- For case 1, SR oscillates around zero (standing). Anti-nodal line stays at constant value.
- For case 2, SR mainly stays in -0.6 (CW), but intermittently switches to 0 (standing) or 0.6 (CCW). Anti-nodal line dominantly rotates in CW, but sometimes in CCW.

Case 1 (standing dominant)



Case 2 (CW dominant)



RESEARCH TASK 2

TASK 2.2 PROGRESS (PRESSURE CHARACTERIZATION)

Phase Portrait in Spin Ratio & Phase Difference Space

- Three different operating conditions were investigated.
- Acquire data for 30 seconds (~ 50,000 cycles) at stabilized operating conditions

1. Remove data points outside two standard deviation of the mean of $(2F^2 + 2G^2)^{1/2}$

2. Divide phase space into $M \times M$ grid. Find all data points satisfying $|SR - SR_i| < \epsilon_{SR}$ and $|\phi - \phi_i| <$ simultaneously (i.e., $\epsilon_{SR} = 2/M$ and $\epsilon_\phi = 2\pi/M$), denoted as $\left(SR_i(t_k), \phi_i(t_k)\right)$

3. Identify phase space evolution of points originating from $\left(SR_i(t_k), \phi_i(t_k)\right)$ after Δt, given by $\left(SR_i(t_k + \Delta t), \phi_i(t_k + \Delta t)\right)$

4. Compute ensemble average of $\left(SR_i(t_k + \Delta t), \phi_i(t_k + \Delta t)\right)$: $\left(\overline{SR}_i(t_k + \Delta t), \bar{\phi}_i(t_k + \Delta t)\right)$

5. Plot vector from $\left(SR_i(t_k), \phi_i(t_k)\right)$ to $\left(\overline{SR}_i(t_k + \Delta t), \bar{\phi}_i(t_k + \Delta t)\right)$

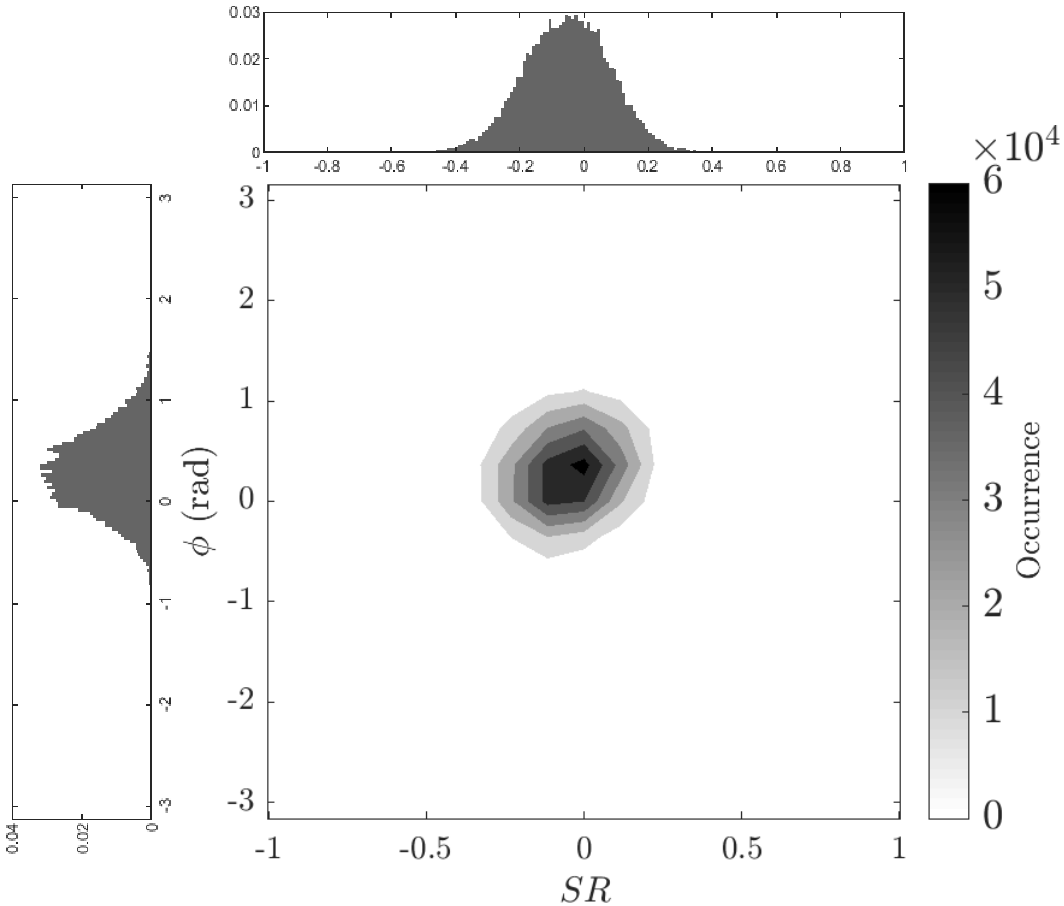
6. Repeat these steps for each SR and ϕ pair, $\left(SR_j(t_k), \phi_j(t_k)\right)$. Results are plotted for all pairs with >100 realizations.

For the results presented here, we used $M = 15$ and $\Delta t = 10$ cycles.

RESEARCH TASK 2

TASK 2.2 PROGRESS (PRESSURE CHARACTERIZATION)

- For case 1, stable attractor appears at the center of the phase portrait.
- CW spiral trajectories.

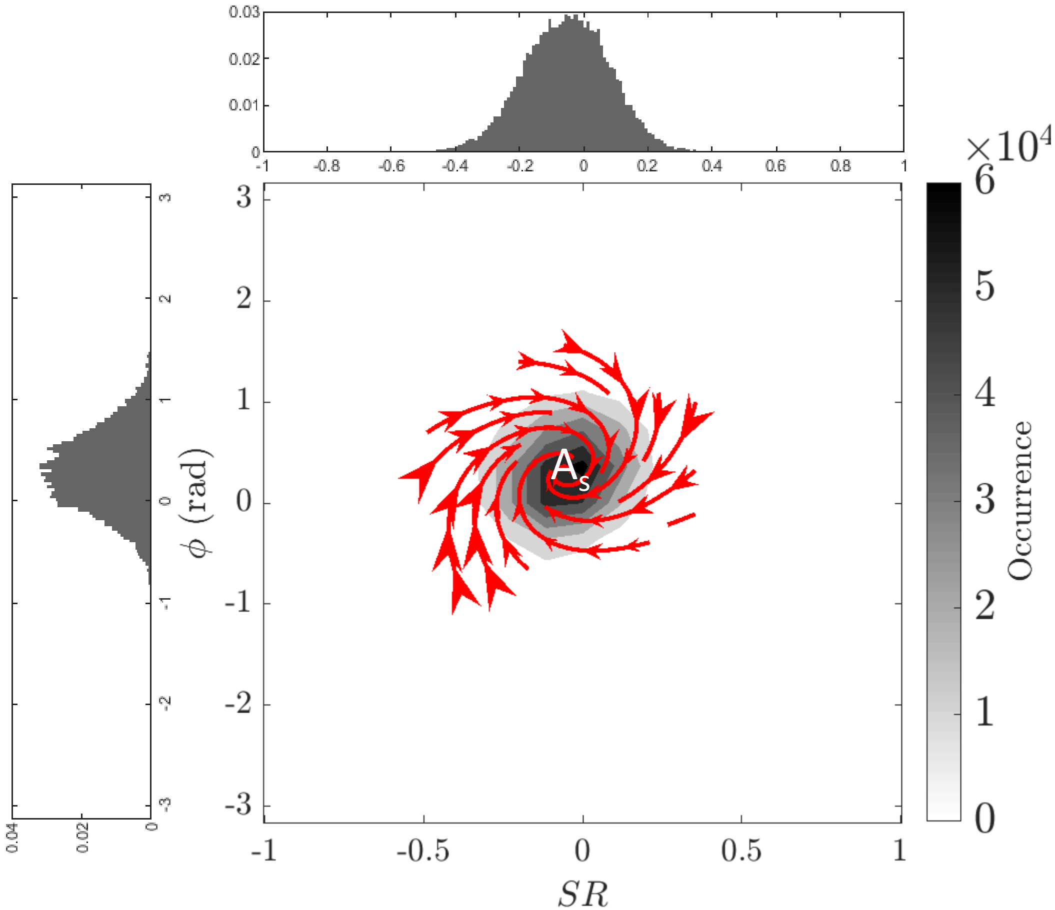


Case 1 (standing dominant)

RESEARCH TASK 2

TASK 2.2 PROGRESS (PRESSURE CHARACTERIZATION)

- For case 1, stable attractor appears at the center of the phase portrait.
- CW spiral trajectories.

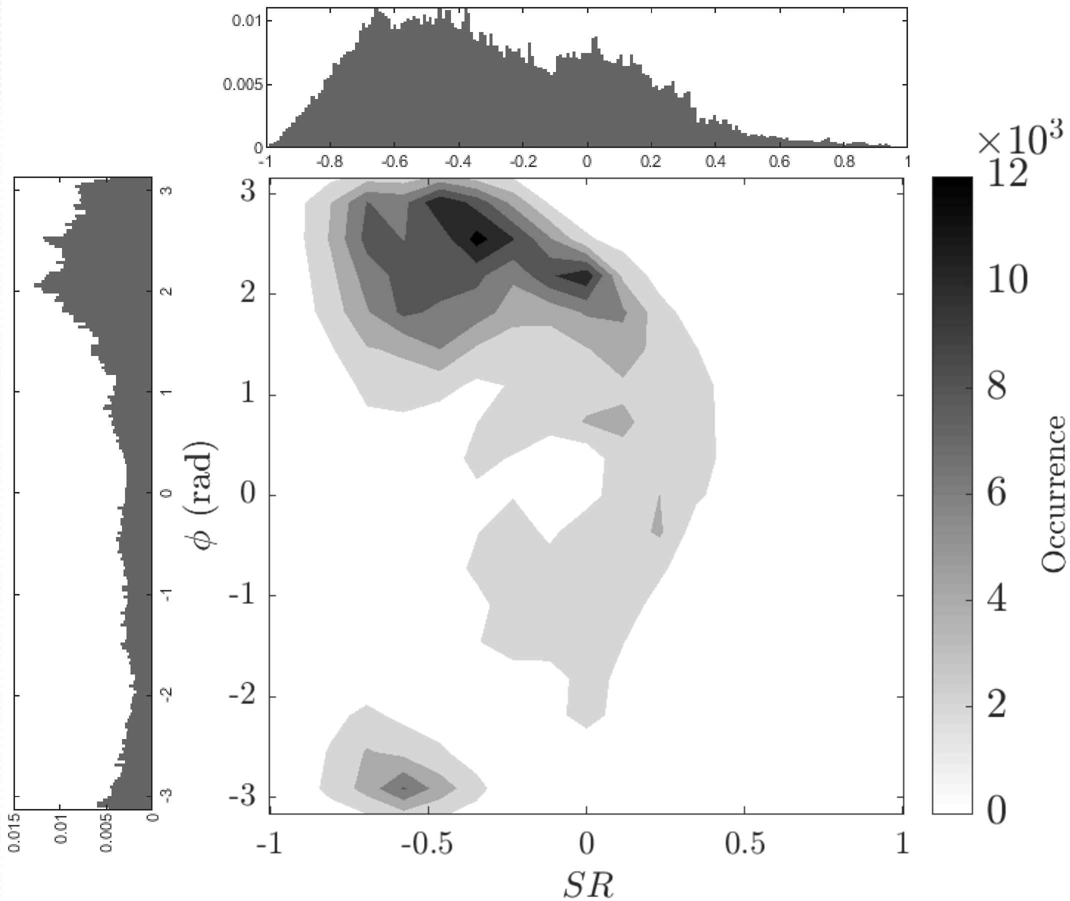


Case 1 (standing dominant)

RESEARCH TASK 2

TASK 2.2 PROGRESS (PRESSURE CHARACTERIZATION)

- For case 2, multiple fixed points and saddle points were observed.
- Most realizations stays at A_{cw}

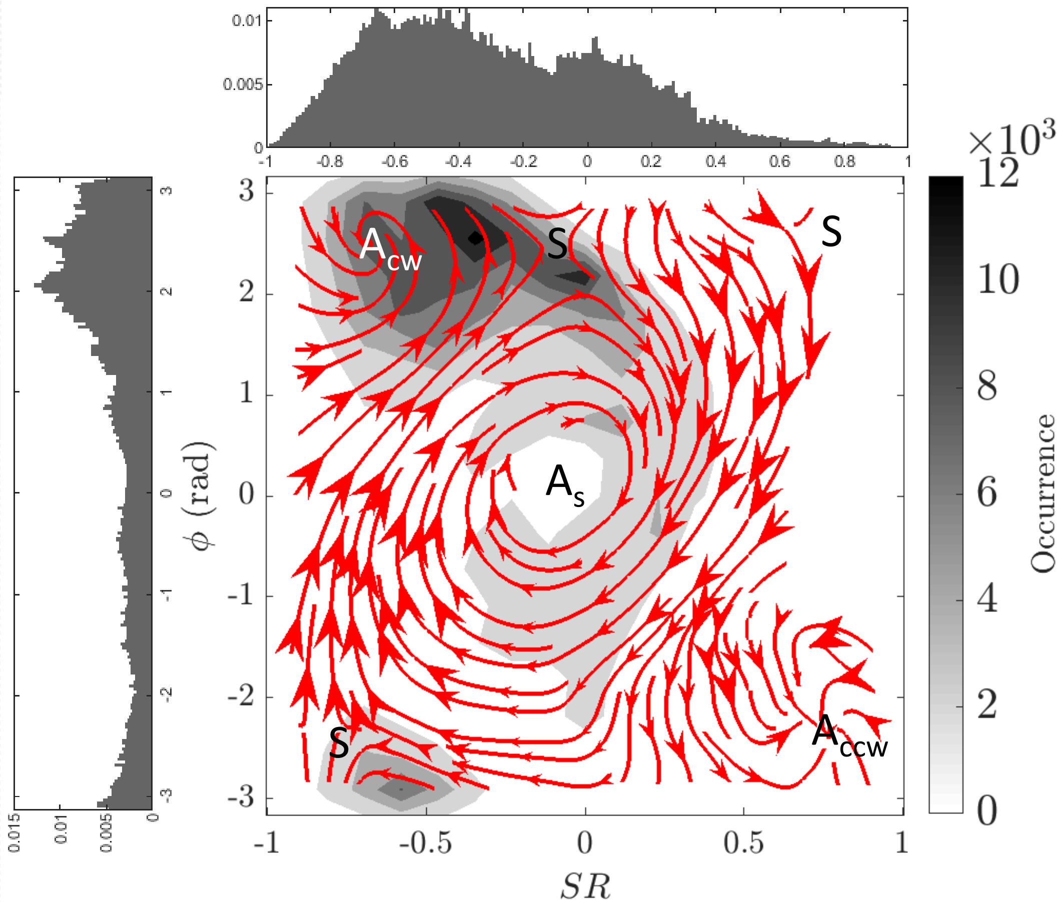


Case 2 (CW dominant)

RESEARCH TASK 2

TASK 2.2 PROGRESS (PRESSURE CHARACTERIZATION)

- For case 2, multiple fixed points and saddle points were observed.
- Most realizations stays at A_{cw}

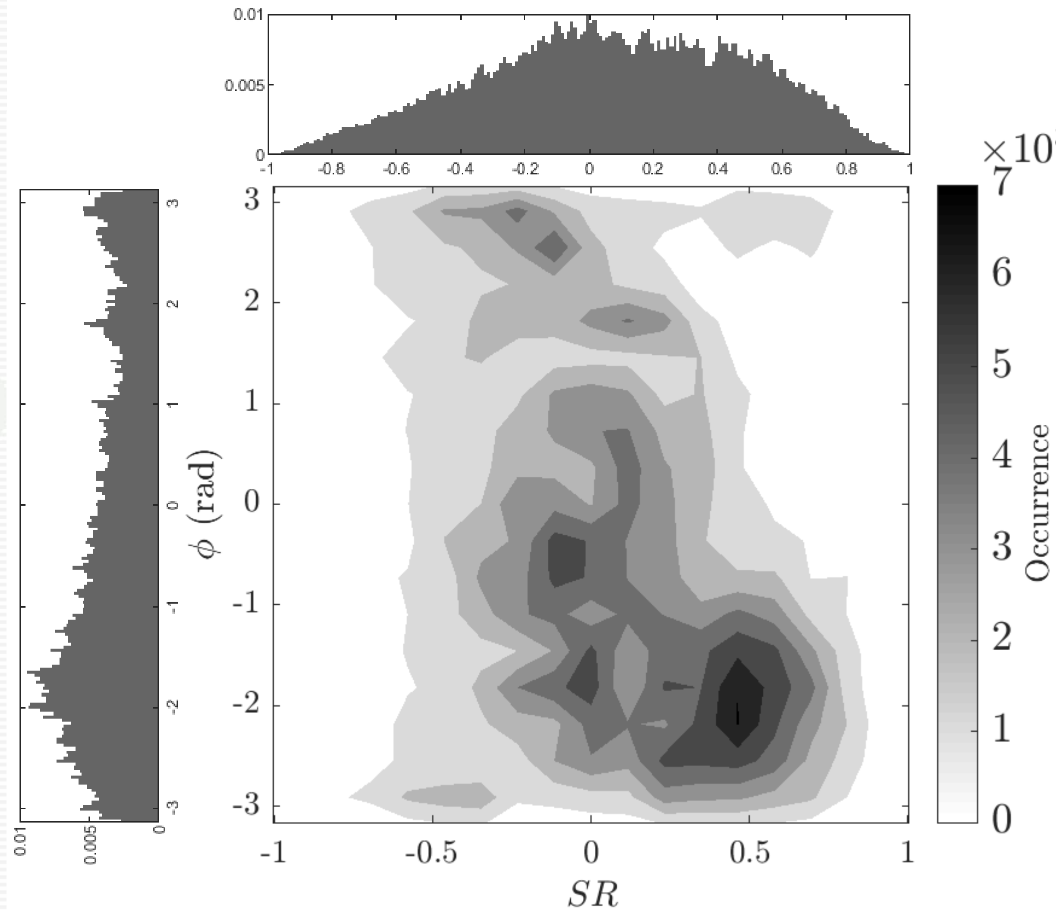


Case 2 (CW dominant)

RESEARCH TASK 2

TASK 2.2 PROGRESS (PRESSURE CHARACTERIZATION)

- For case 3, multiple fixed points and saddle points were observed.
- Most realizations stays at A_{ccw}

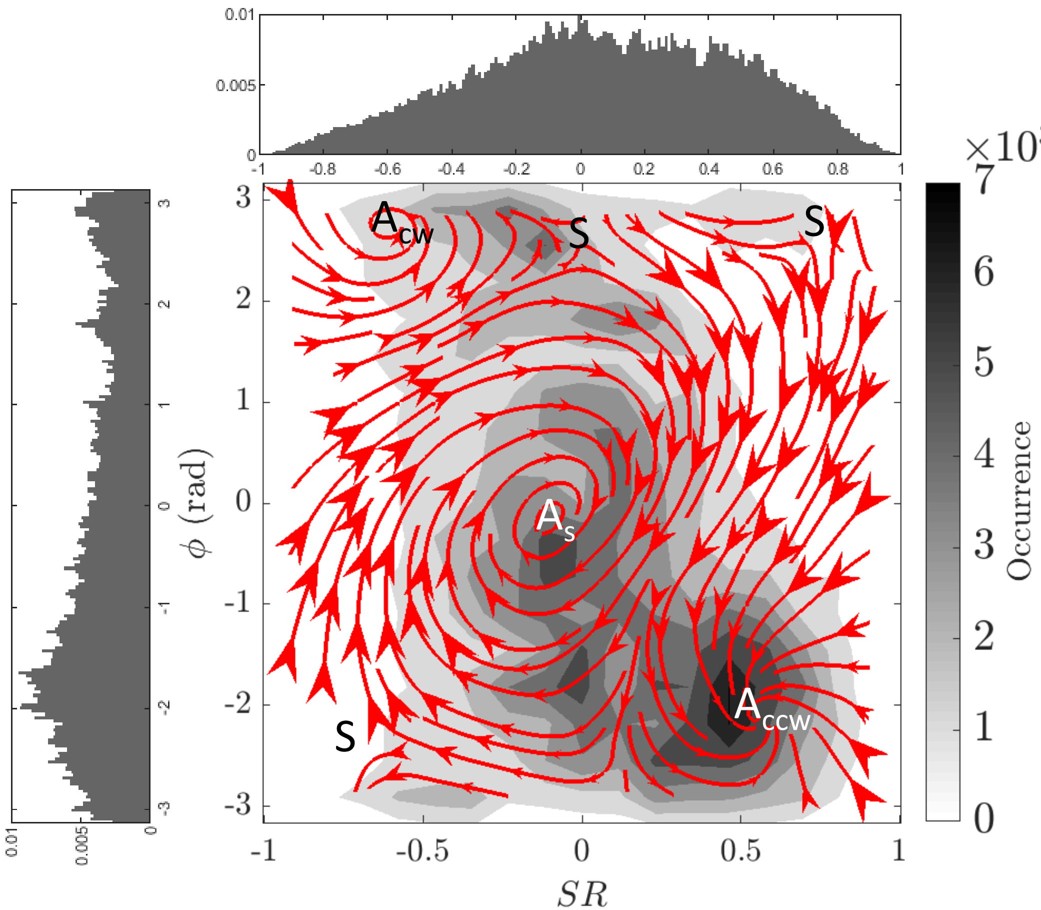


Case 3 (CCW dominant)

RESEARCH TASK 2

TASK 2.2 PROGRESS (PRESSURE CHARACTERIZATION)

- For case 3, multiple fixed points and saddle points were observed.
- Most realizations stays at A_{ccw}



Case 3 (CCW dominant)

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

Single point pressure measurements show pressure amplitudes with variety of characteristics (relatively constant, varying significantly, etc.)

Developed suite of system identification tools for extraction of nodal line position/velocity, spin ratio, amplitude

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

Observed coherent structure from CH* phase averaged images, suggesting potential mechanism of transverse instability.

RESEARCH TASK 3

REDUCED ORDER MODELING FOR THERMOACOUSTIC COUPLING

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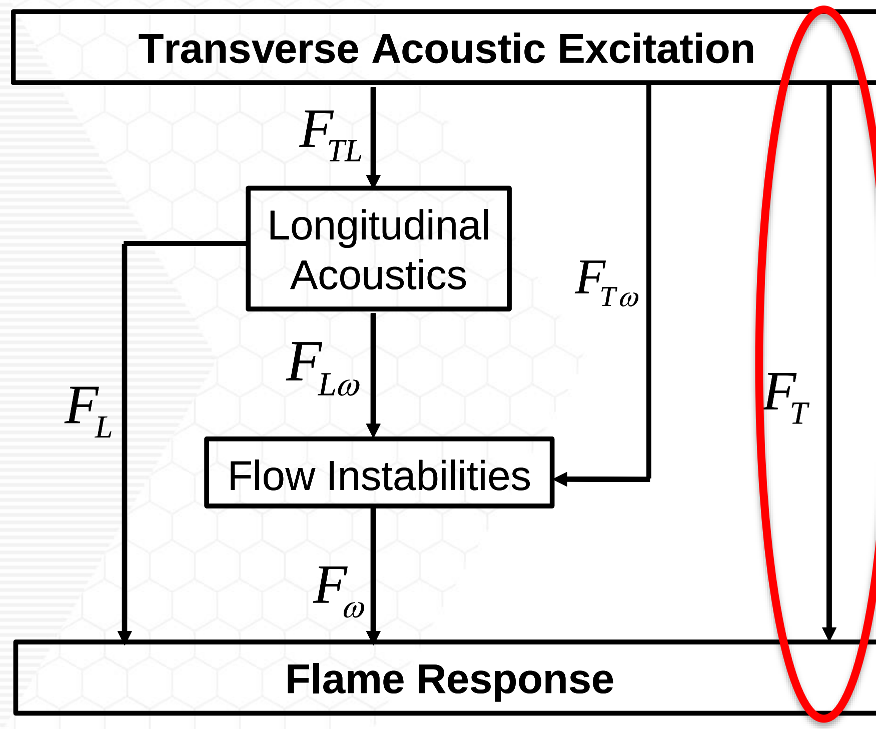
RESEARCH TASK 3.1 PROGRESS

VELOCITY COUPLED FLAME RESPONSE

- Direct excitation by transverse acoustic velocity disturbances F_T
- Indirect excitation through
  - F_{TL} – Excited longitudinal acoustics
  - $F_{T\omega}$ – Transverse acoustics directly excites inherent flow instabilities
  - $F_{L\omega}$ – Transverse acoustics indirectly excites flow instabilities

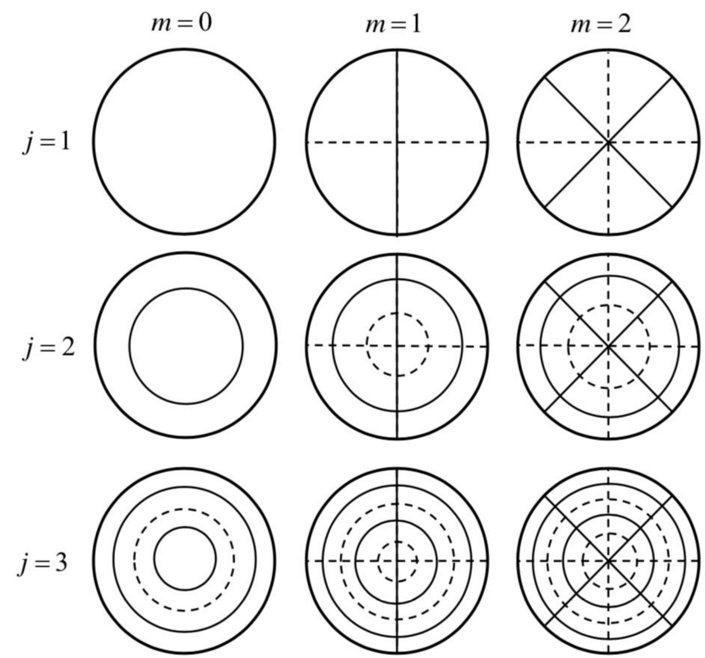
FOCUS – DIRECT EXCITATION MECHANISM EFFECTS



RESEARCH TASK 3.1 PROGRESS

RESEARCH QUESTIONS

- **What are the relative stabilities for different high-frequency transverse acoustic modes?**
- **Stability boundaries?**
- **How do different nozzles in the combustor contribute to stability/instability for the same acoustic mode? (nozzle position, flame shape)**



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 PROGRESS

IMPLICATIONS ON 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:

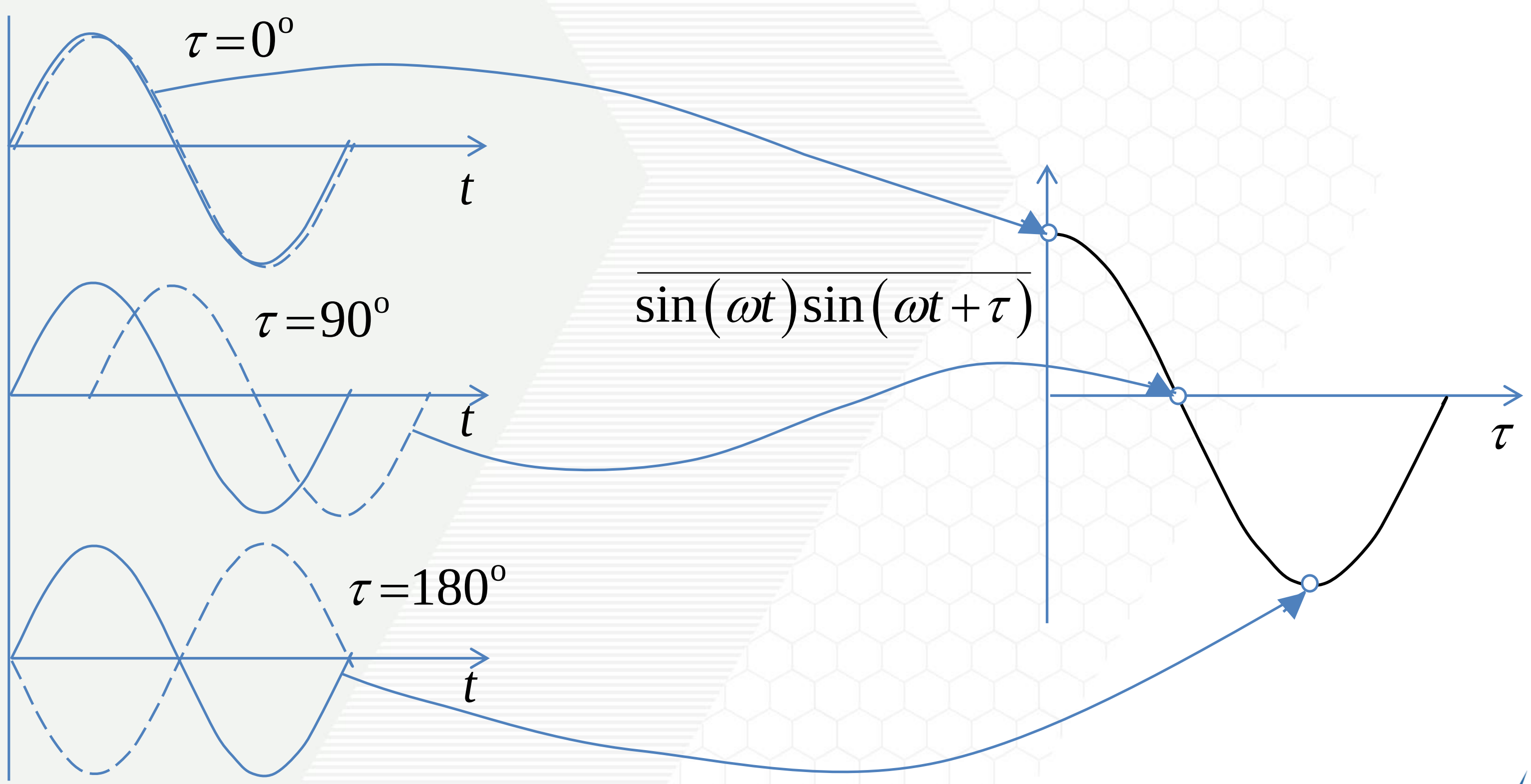
$$\boxed{RI = \int_t \int_V p_1 \dot{q}_1 dV dt > 0}$$

RESEARCH TASK 3.1 PROGRESS

RAYLEIGH CRITERION MECHANICS FOR COMPACT FLAMES

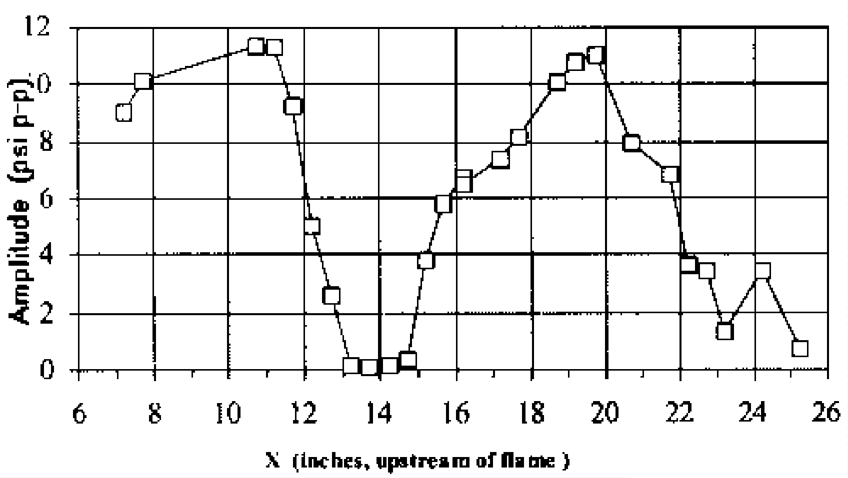
- RI → Time average of product of two fluctuating quantities
- Sign of RI depends on relative phasing of fluctuating quantities

Example $\overline{\sin(\omega t)\sin(\omega t+\tau)} = \frac{1}{2}\cos\tau$



RESEARCH TASK 3.1 PROGRESS

RAYLEIGH CRITERION – COMPACT FLAMES AXIAL INSTABILITIES



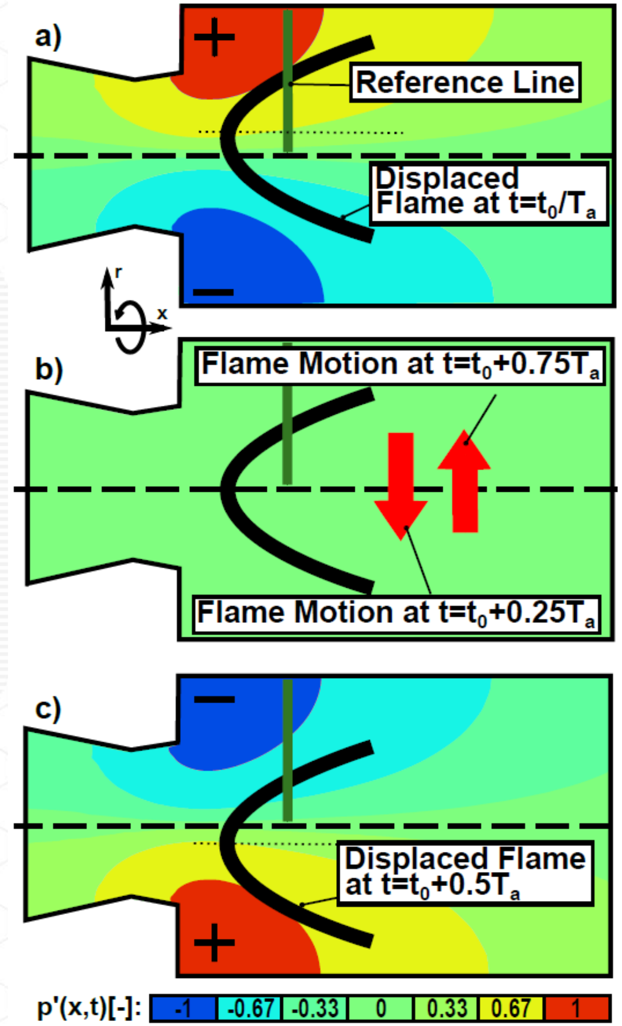
From Lovett, J., and Uznanski, K., Prediction of Combustion Dynamics in a Staged Premixed Combustor, ASME Paper # 2002-GT-30646

- Data shows “instability bands” of a single mode
  - instabilities depend upon convective time

RESEARCH TASK 3.1 PROGRESS

PRIOR WORK ON DIRECT EXCITATION (SATTELMAYER & CO-WORKERS)

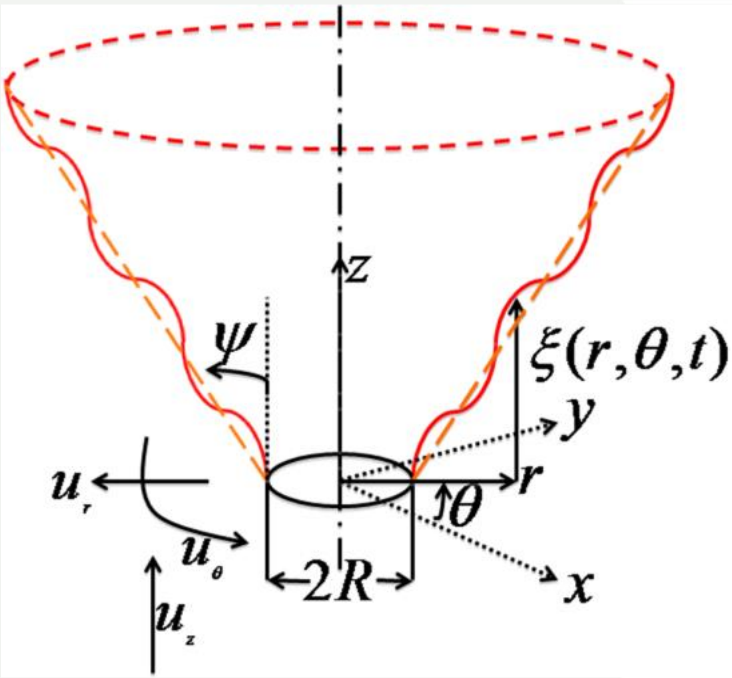
- Phenomenological argument in 2D, using flame displacement mechanism arguments
- Modes are unconditionally unstable for thermoacoustic coupling
  - No stability bands!



Reproduced from Hummel et al., GT2016-57500

RESEARCH TASK 3.1 PROGRESS

DIRECT EXCITATION MODELING IN THIS DOE PROGRAM



- Level-set for a thin premixed flame

$$\boxed{\frac{\partial G}{\partial t} + \vec{u}\cdot\vec{\nabla}G = s_L\left|\vec{\nabla}G\right|}$$

- Explicit flame dynamics

$$G(r,\theta,z,t) = z - \xi(r,\theta,t)$$

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

  - Single-valued flame position
  - Flame is a thin interface
  - Constant flame speed
  - Imposed velocity disturbances

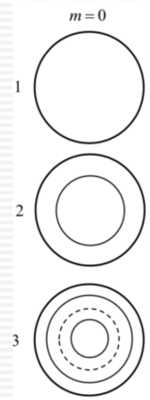
- Normalized Rayleigh Index

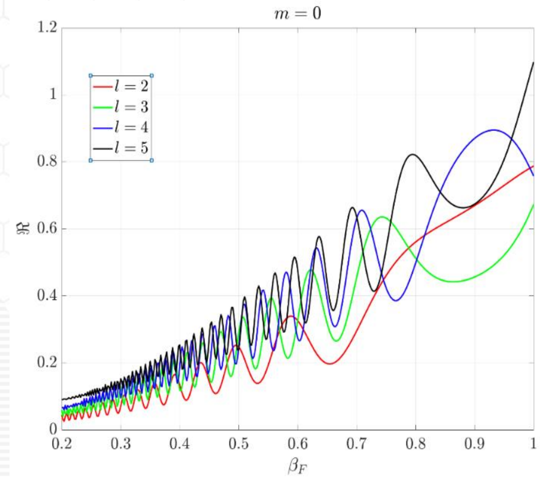
$$\boxed{\Re = \frac{RI}{2E}}$$

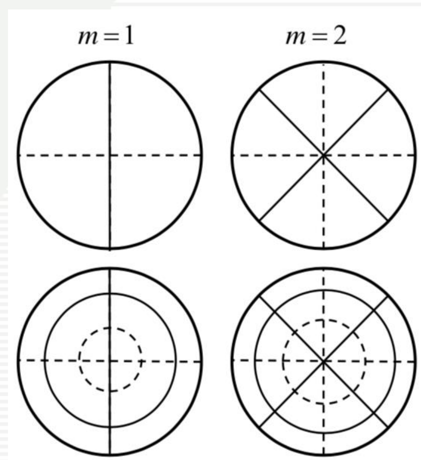
RESEARCH TASK 3.1 PROGRESS

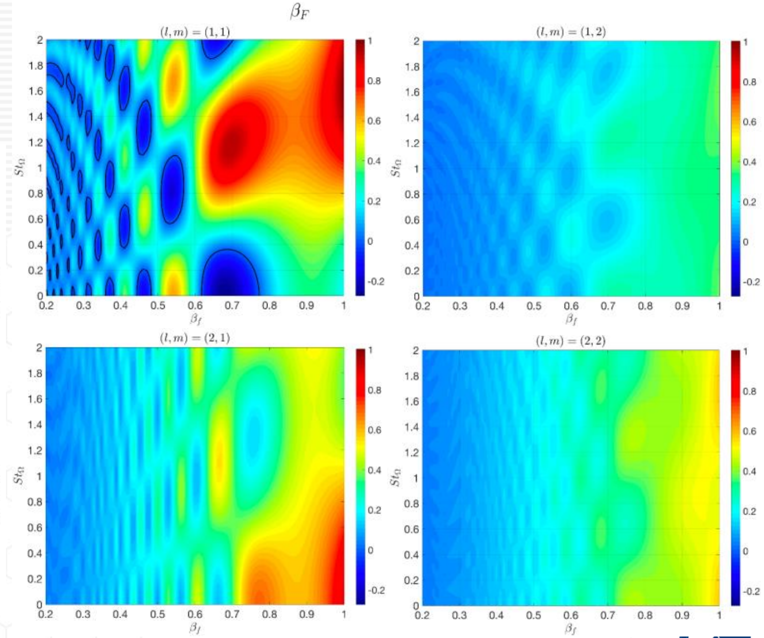
RESULTS – COMBUSTOR CENTERED AXISYMMETRIC FLAME

- Acharya & Lieuwen, AIAA SciTech 2018
- 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



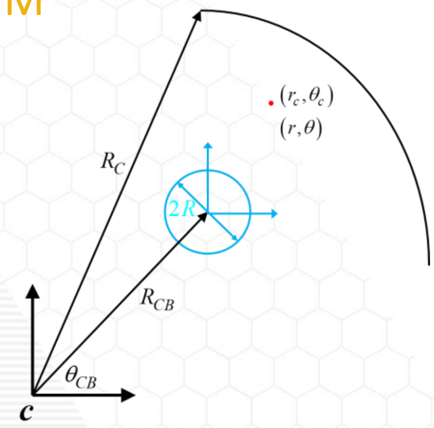






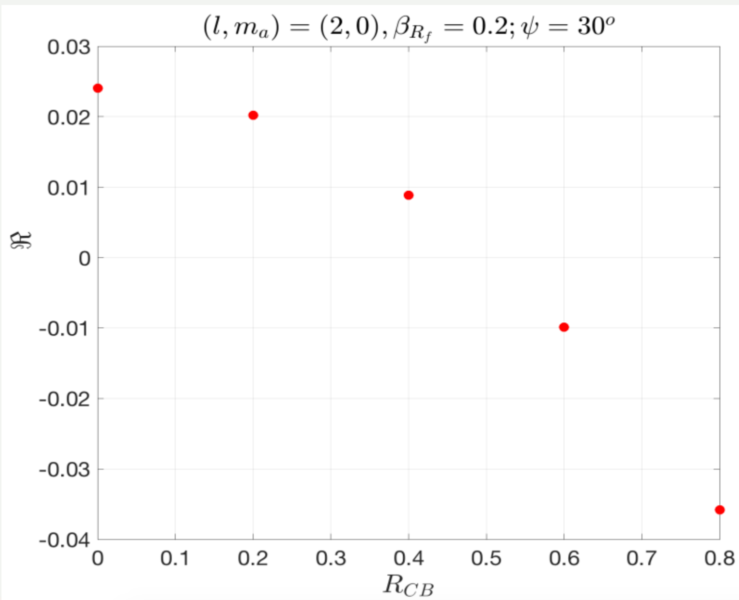
RESEARCH TASK 3.1 PROGRESS

RESULTS – STABILITY OF FLAMES OFFSET FROM COMBUSTOR AXIS

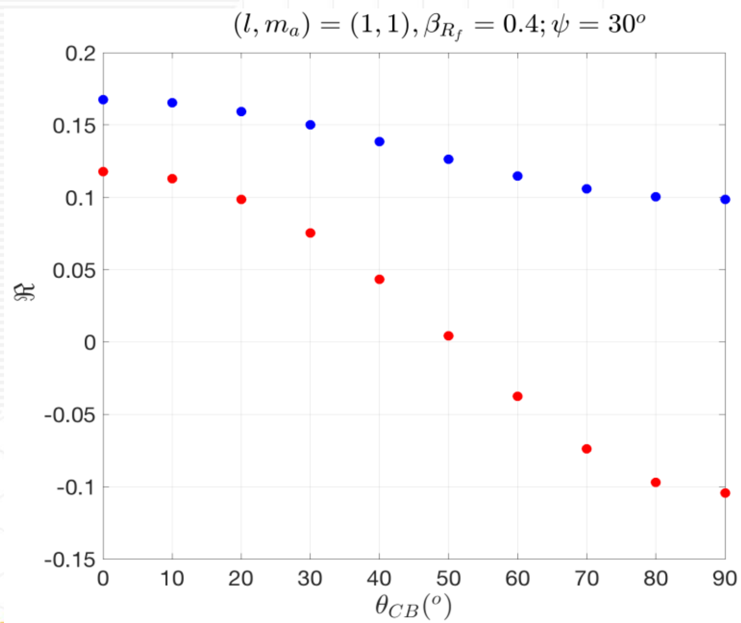


- Acharya & Lieuwen, ESSCI 2018
- Flame location relative on mode shape affects RI
  - Nozzle offset from axis implies, local azimuthal acoustic velocity affects RI

Outward radial offset increases stability



Azimuthal offset increases stability



RESEARCH TASK 3.1 PROGRESS

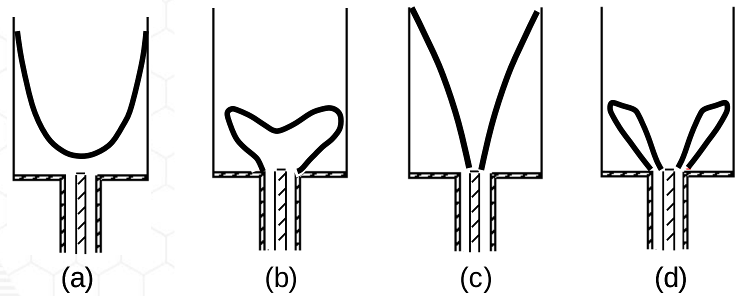
TAKEAWAYS & FUTURE WORK

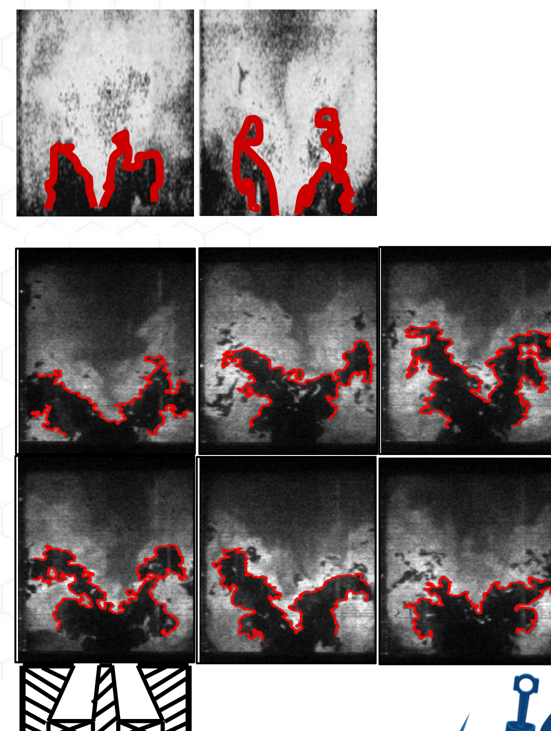
- Key Takeaways
  - Axisymmetric Mean Flame
    - Combustor centered flame – local acoustic azimuthal velocity does not directly influence RI
    - Offset flame – local acoustic azimuthal velocity affects RI indirectly.
  - Radial mode unconditionally unstable
  - Mixed mode (1,1) has islands of stability, other modes relatively unstable
  - Radial and azimuthal offset increases stability
- **ON-GOING WORK**
  - **What happens when mean flame is non-axisymmetric?**
  - **What are the stability sensitivities? How do small changes in different control parameters affect RI?**

RESEARCH TASK 3.2 PROGRESS

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 PROGRESS

HYDRODYNAMIC STABILITY MODELING

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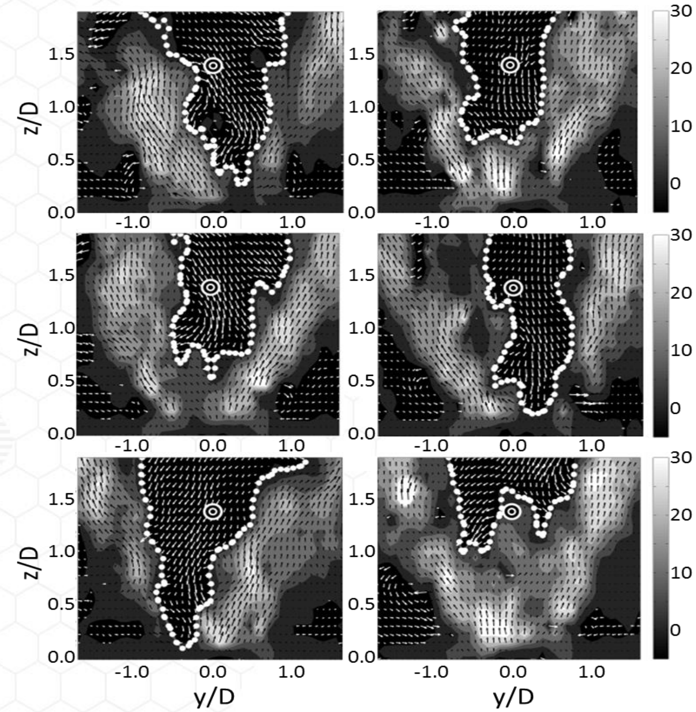
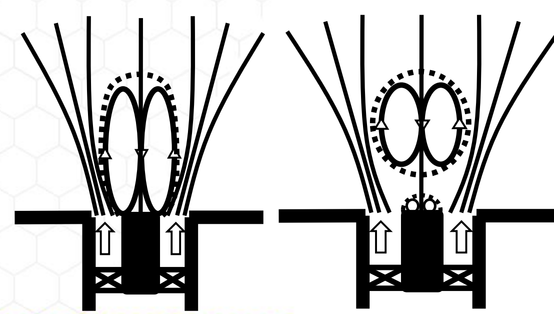


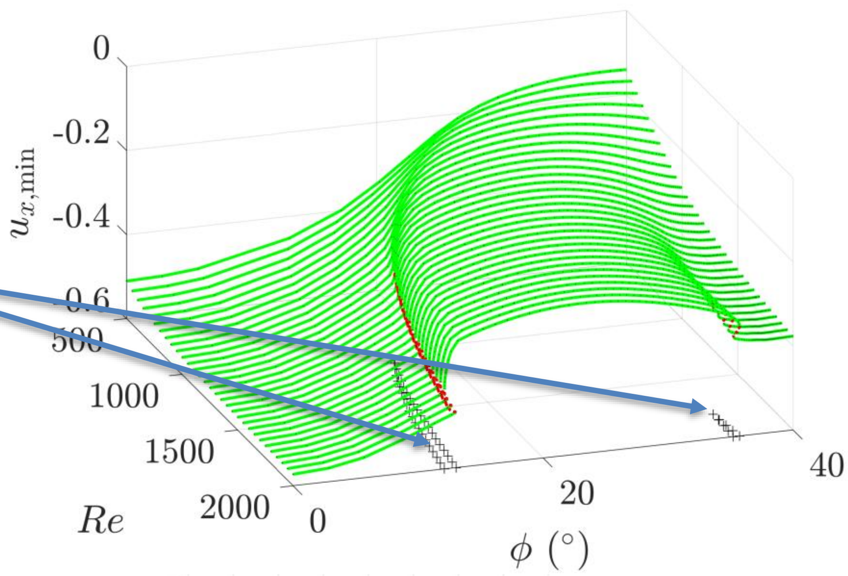
- Under what circumstances can such flames exist?
  - Not always observed; flames may blowoff directly without reverting to a “free floating” configuration
  - Flow must have interior stagnation point

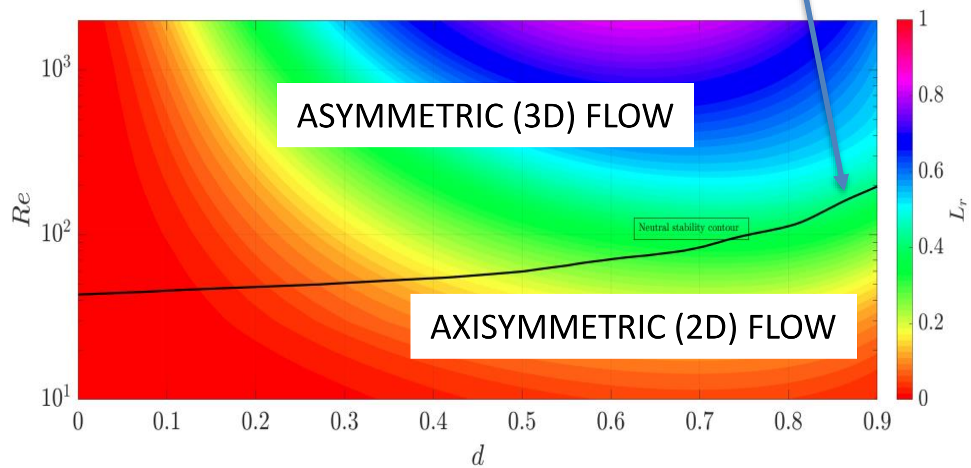


RESEARCH TASK 3.2 PROGRESS

HYDRODYNAMIC STABILITY MODELING

- Fundamental understanding of flow dynamics starts in the laminar regime.
- Nonlinear bifurcation analysis
  - Saddle-node bifurcations -> hysteresis
  - Pitchfork bifurcations -> symmetry-breaking
  - Hopf bifurcations -> limit cycles



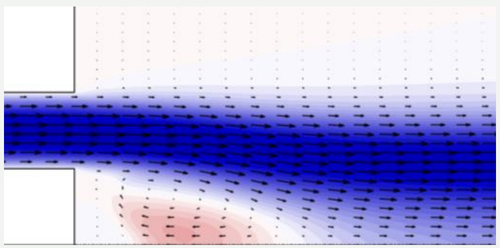
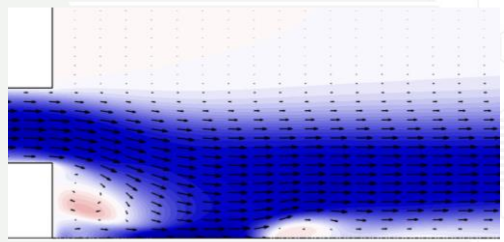
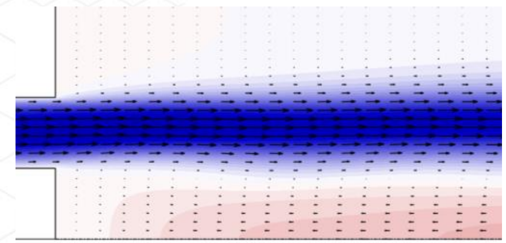
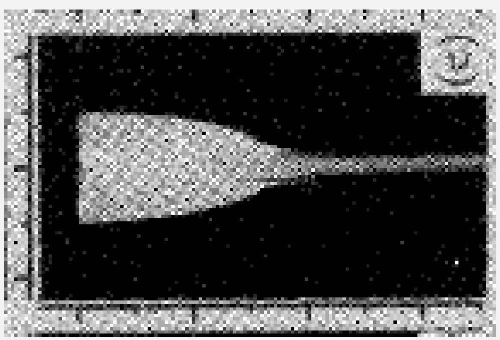
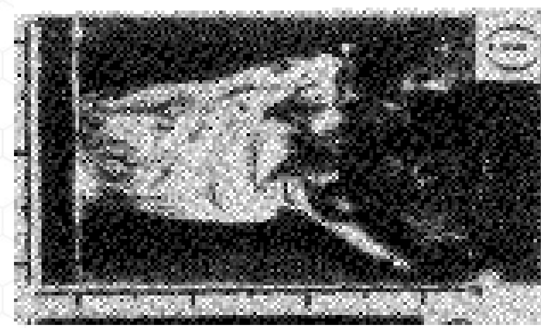


<u>When are certain families of solutions possible?</u>

RESEARCH TASK 3.2 PROGRESS

HYDRODYNAMIC STABILITY MODELING

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

	Recirculation zone with vortex tube	Recirculation zone with bubble-like breakdown above	Merged recirculation zones
BASE FLOW			
EXPERIMENT			

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

Swirl number

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RESEARCH TASK 3.2 PROGRESS

TAKEAWAYS & FUTURE WORK

- Key Takeaways
  - Flame shape and stabilization cannot be predicted reliably without excellent understanding of underlying fluid mechanics.
  - Early results indicate that even simple steady laminar flows can exhibit strong hysteresis and three-dimensionality which drives further complexity at higher *Re*.
  - Much more to come here...
- **ON-GOING WORK**
  - **How do flow geometry and confinement influence steady/time-average dynamical behavior of nonreacting swirling flow systems?**
  - **How does the dynamical picture change in the presence of a reacting flow?**

CONCLUDING REMARKS

- Developed a multi-nozzle can combustor for studying high-frequency instabilities
  - Wide range of operating conditions and pressures.
  - Multiple pressure sensors to simultaneously capture time-varying pressure
  - Development of modal identification methods for determining the transverse modes using pressure data
  - Identification of mode behaviors by comparing clockwise and counter-clockwise modes in phase space.

- High-frequency flame response modeling
  - Developed a model for direct excitation of flames to high-frequency acoustic modes: Model helps understand the effect of flame position in can as well as flame shape, on mode stability
  - Additional models for coupling mechanisms unique to high-frequency instabilities are in development
    - Pressure coupling effects
    - High-frequency hydrodynamics and its coupling with acoustics and heat release