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

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COPI – WENTING SUN

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OUTLINE

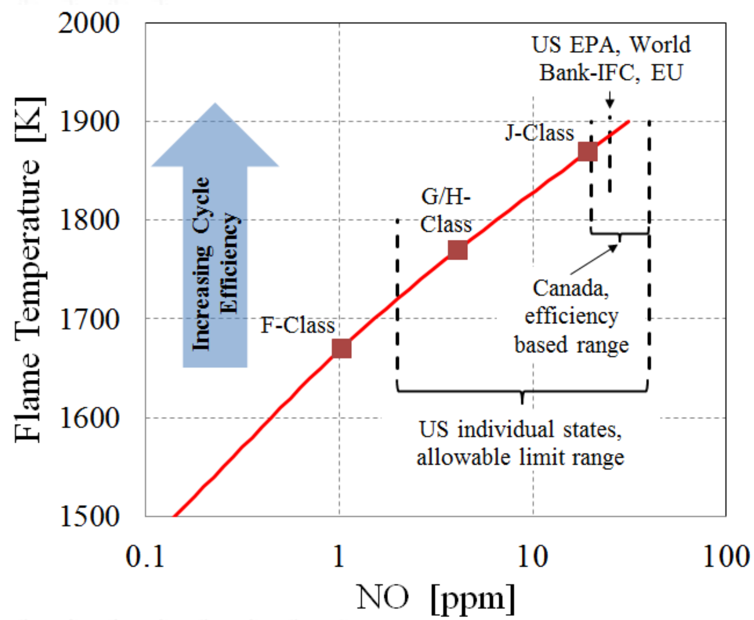
- Motivation for Proposed Research
- Technical background
- Proposed work & Research Progress
  - Task 1: Project management & planning (PMP)
  - Task 2: Experiments on self-excited transverse instabilities
  - Task 3: Reduced order modeling for thermoacoustic coupling
- Program schedule

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

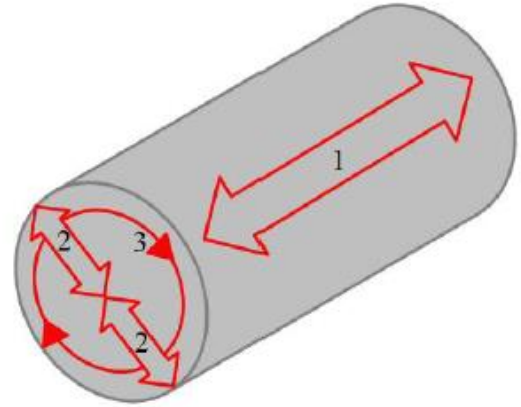
- <u>Focus of the proposed project</u> → **High-frequency transverse combustion instabilities in multi-nozzle can combustor configurations.**

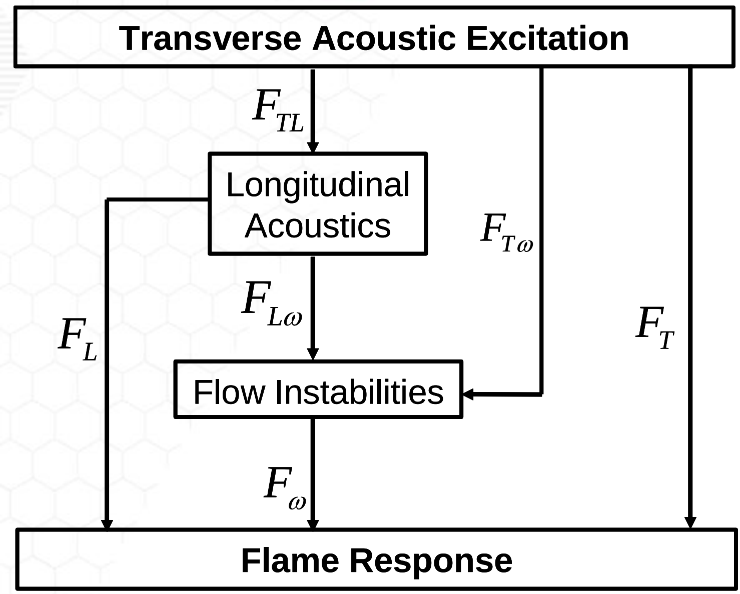


Realistic multi-nozzle experiments and high frequency modeling capabilities needed

TECHNICAL BACKGROUND
TRANSVERSE INSTABILITIES

- **Combustion instability**
  - Coupling between resonant combustor acoustics and heat release rate fluctuations
  - Pressure oscillations can be detrimental to hardware lifetime and emissions.
- **Acoustics**
  - Acoustic wave motions perpendicular relative to main flow direction
    - intrinsic non-axisymmetric excitation
    - No net mass flow modulation of reactants
  - Acoustic wavelength of the order of heat release zone extent.
  - Acoustics excites flame through various pathways

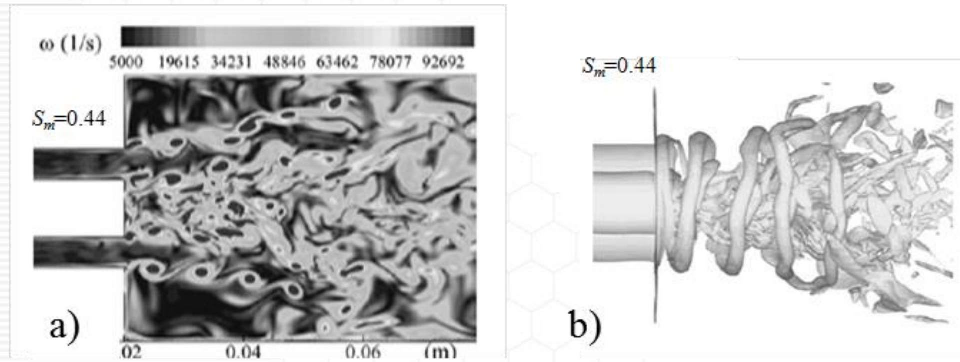


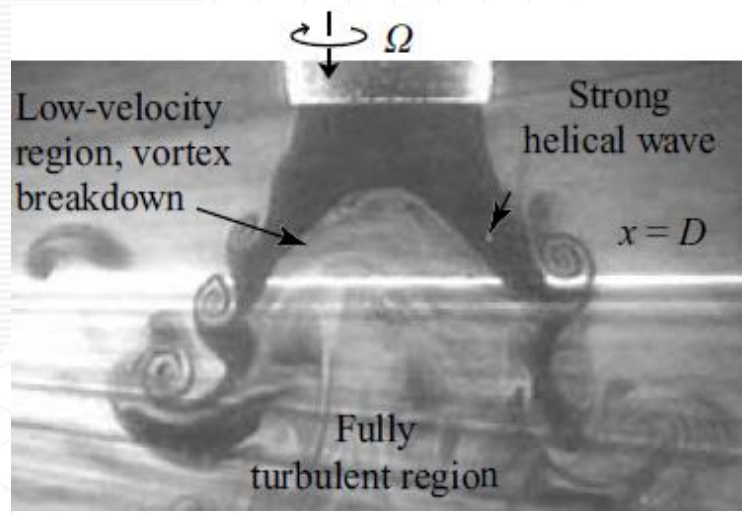


TECHNICAL BACKGROUND
HYDRODYNAMIC INSTABILITIES

- Acoustics excites dynamical flow structures
  - Shear layers
  - Vortex breakdown bubble; PVC

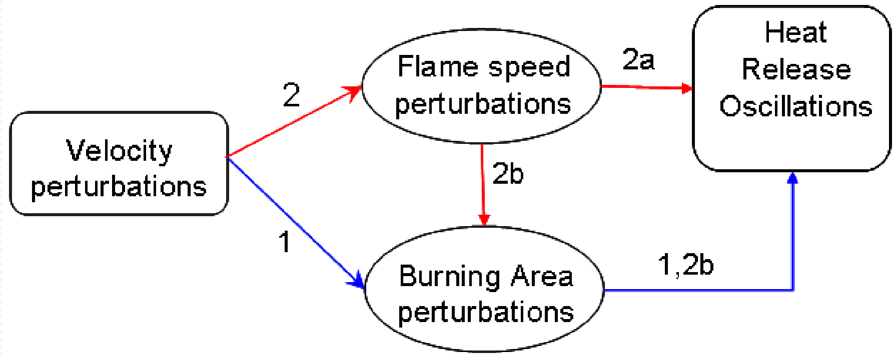
- Sensitivity of disturbances to frequency, amplitude is a function of type of instability, flow features
  - Convective vs. Absolute instability

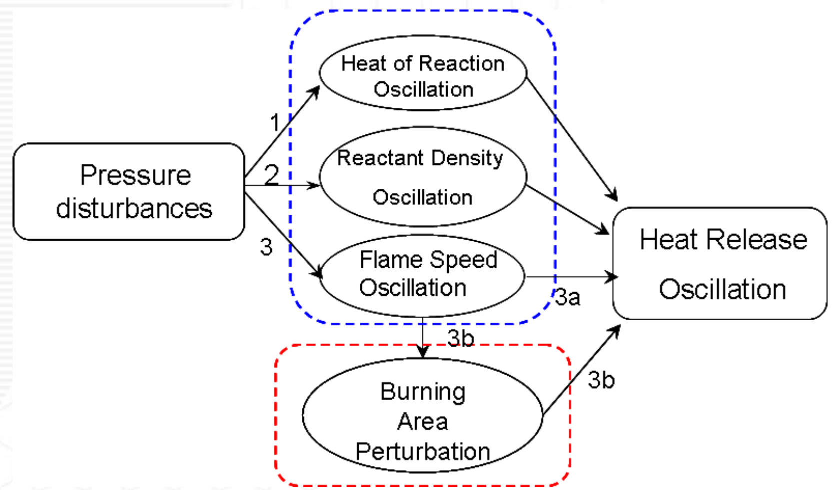




TECHNICAL BACKGROUND
FLAME RESPONSE PATHWAYS

- 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





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?

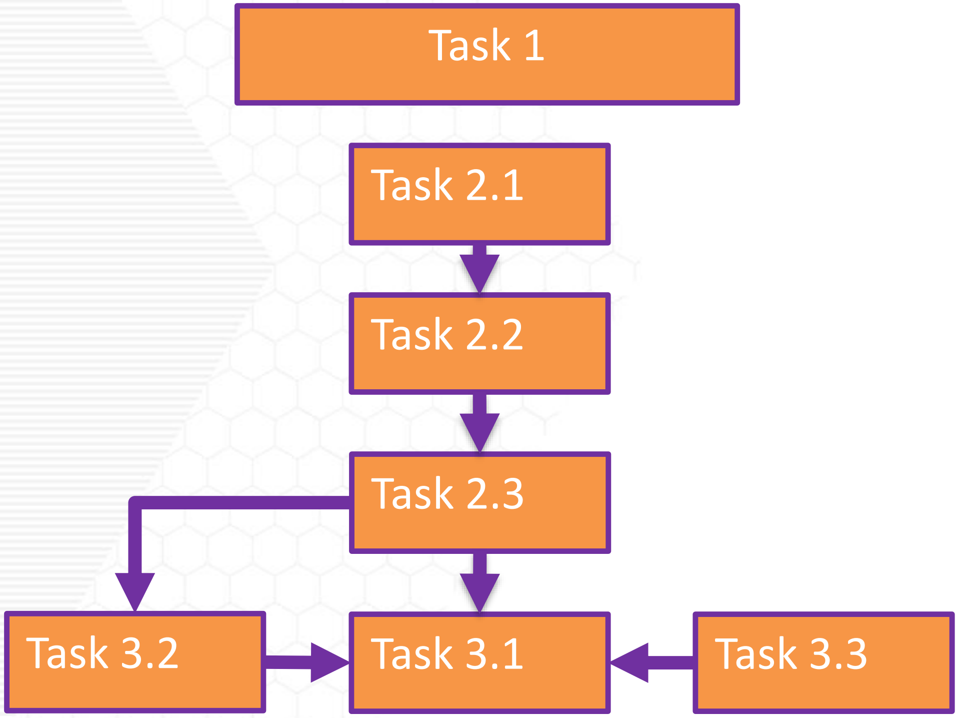
(4) How does the direct effect of pressure fluctuations influence the thermoacoustic stability of the system?

PROJECT PARTICIPANTS

- Lead Principal investigator (PI) – Prof Tim Lieuwen
- Co-Principal Investigator (COPI) – Prof Wenting Sun
- Collaborators & research engineers
  - Vishal Acharya
  - Benjamin Emerson
  - David Wu
- Graduate students
  - One graduate student advised by Prof. Lieuwen
  - One graduate student advised by Prof. Sun
- 3 Undergraduate students assisting graduate students and research engineers

TASKS & CONNECTIONS

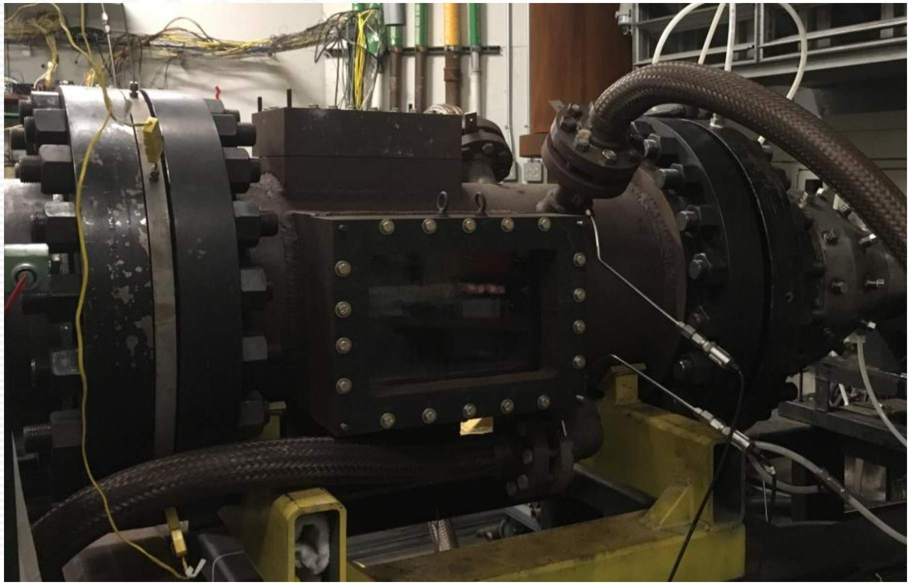
- Task 1: PMP
- Task 2: Experiments on self-excited transverse instabilities
  - 2.1 – Design of Experiment
  - 2.2 – Pressure characterization
  - 2.3 – Flow and flame characterization
- Task 3: Reduced order modeling for thermoacoustic coupling
  - 3.1 – Flame response modeling
  - 3.2 – Hydrodynamic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

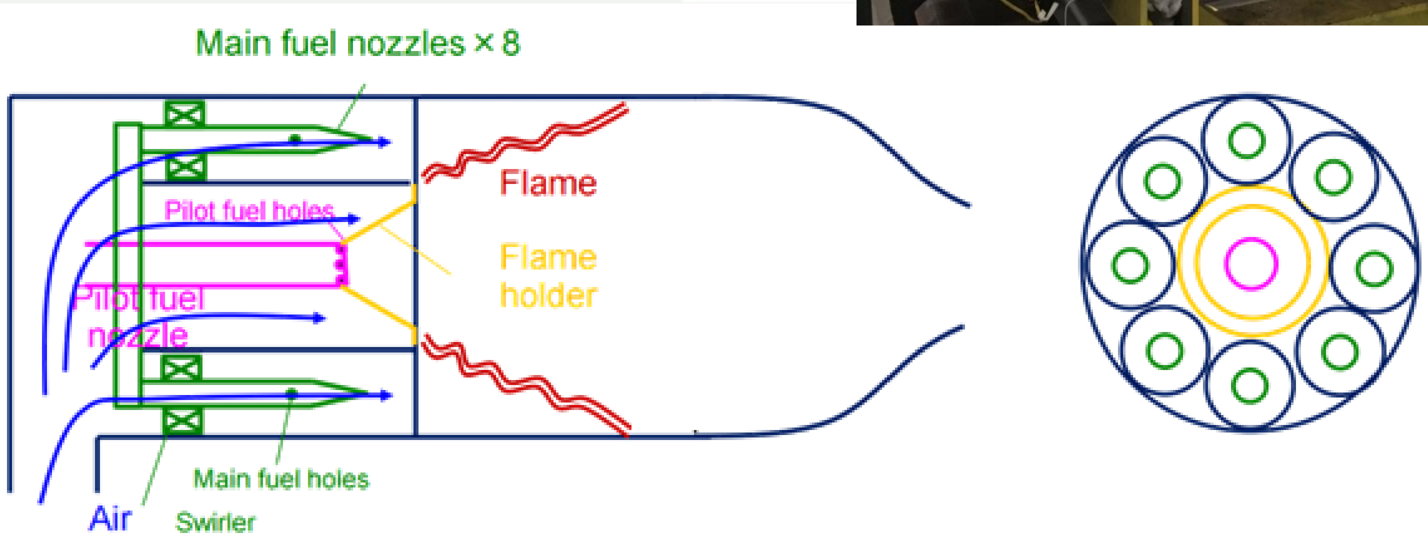


RESEARCH TASK 2

DESIGN OF EXPERIMENT FOR SELF-EXCITED TRANSVERSE INSTABILITIES

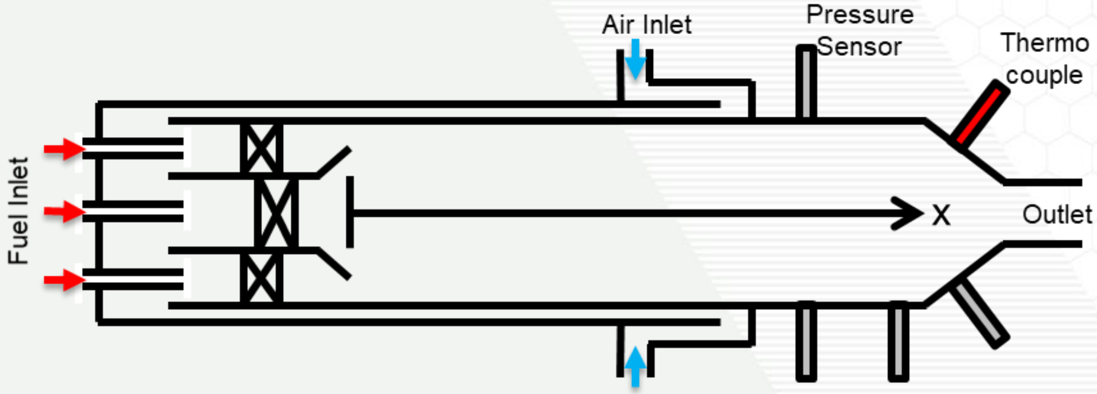
- Task 2.1: Design of experiment
  - Design realistic multi-nozzle can combustor with optical access
  - Test facility for self-excited acoustics
  - See poster for further details





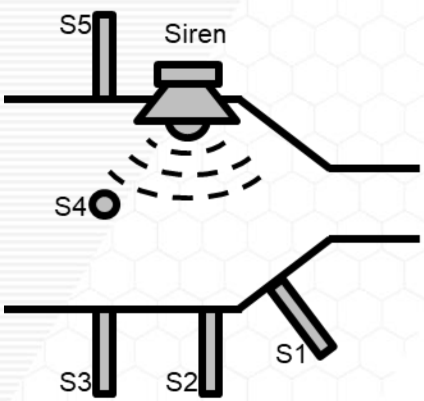
RESEARCH TASK 2

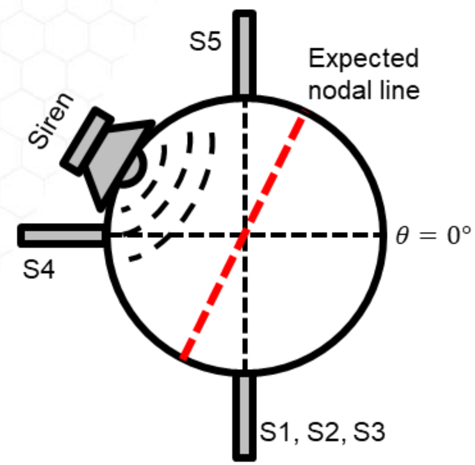
TASK 2.1 PROGRESS (EXPERIMENTAL COMBUSTOR)



- Design a facility with realistic diameter combustor
  → capture accurate high-frequency acoustics.
- Multiple nozzles
  → capture flame-flame interactions.
- Optical accessibility using quartz
  → spatio-temporal flow and flame characterization
- Flexibility
  → multiple fuel circuits.

- External excitation
  → use a siren to excite longitudinal and transverse mode.
- Multiple sensors
  → mount five sensors at different axial and azimuthal location.
- Acoustic mode identification
  → Verify the acoustic mode shape generated by the siren





RESEARCH TASK 2

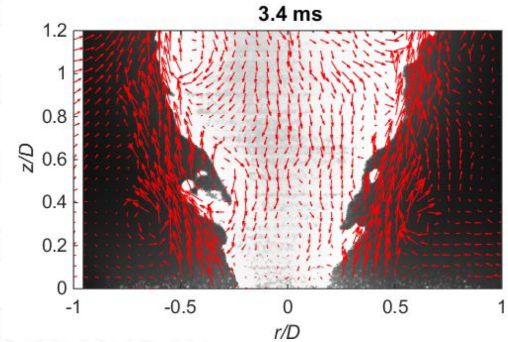
DESIGN OF EXPERIMENT FOR SELF-EXCITED TRANSVERSE INSTABILITIES

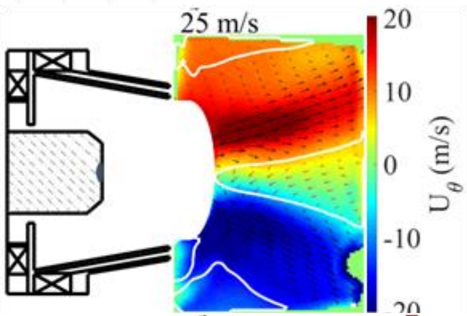
<u>Task 2.2: Spatio-temporal characterization of unsteady pressure</u>

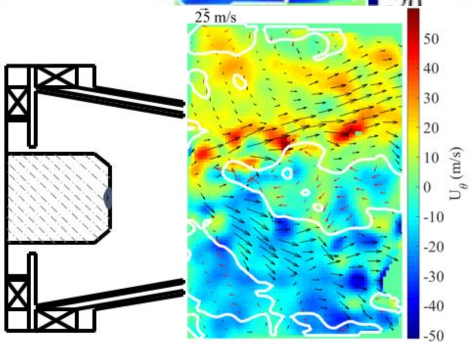
- Identify acoustic modes
- FEM for acoustic modes
  - Identifies necessary number and location of acoustic sensors
  - Helps differentiate between modes with similar frequencies i.e. Spinning vs. standing or transverse vs. longitudinal

<u>Task 2.3: Optical diagnostics for unsteady flow and flame characterization</u>

- Laser-based diagnostics to study interaction between combustion, acoustics, and fluid dynamics
  - High speed chemiluminescence, s-PIV, and OH-PLIF







RESEARCH TASK 2

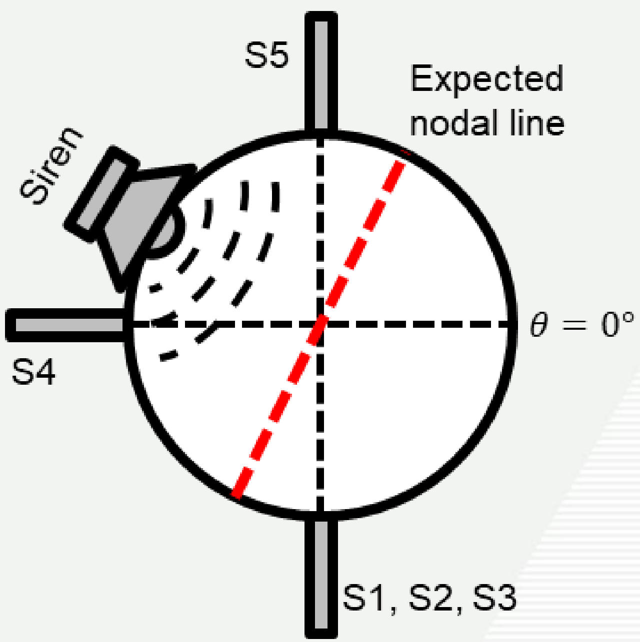
TASK 2.2 PROGRESS (DATA AND METHODS FOR ANALYSIS)

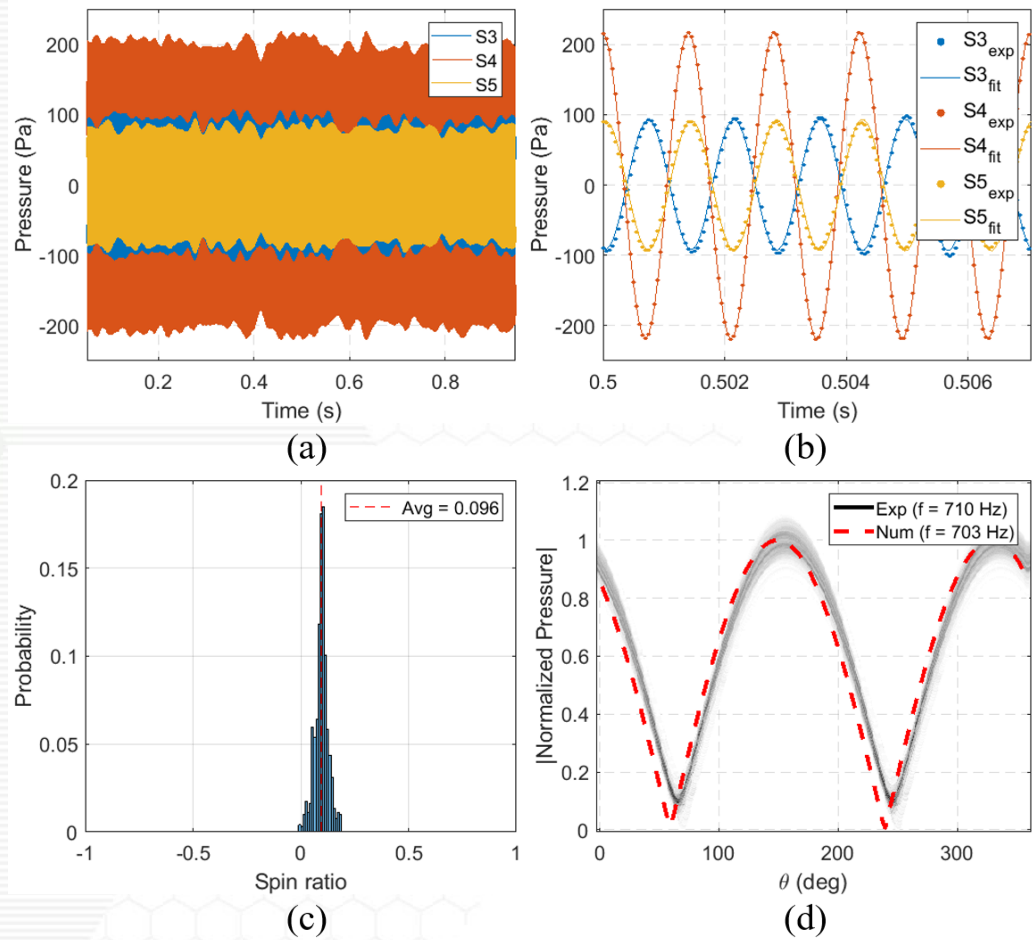
Azimuthal dependency

- PDF of spin ratio

→ centered near zero (standing mode)

→ 1 nodal line (1-T mode)





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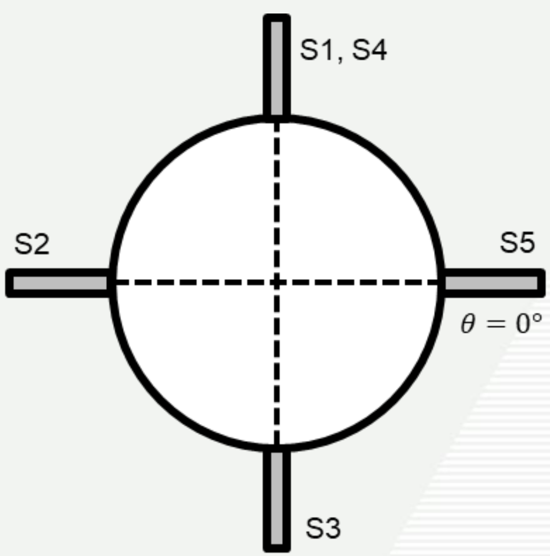

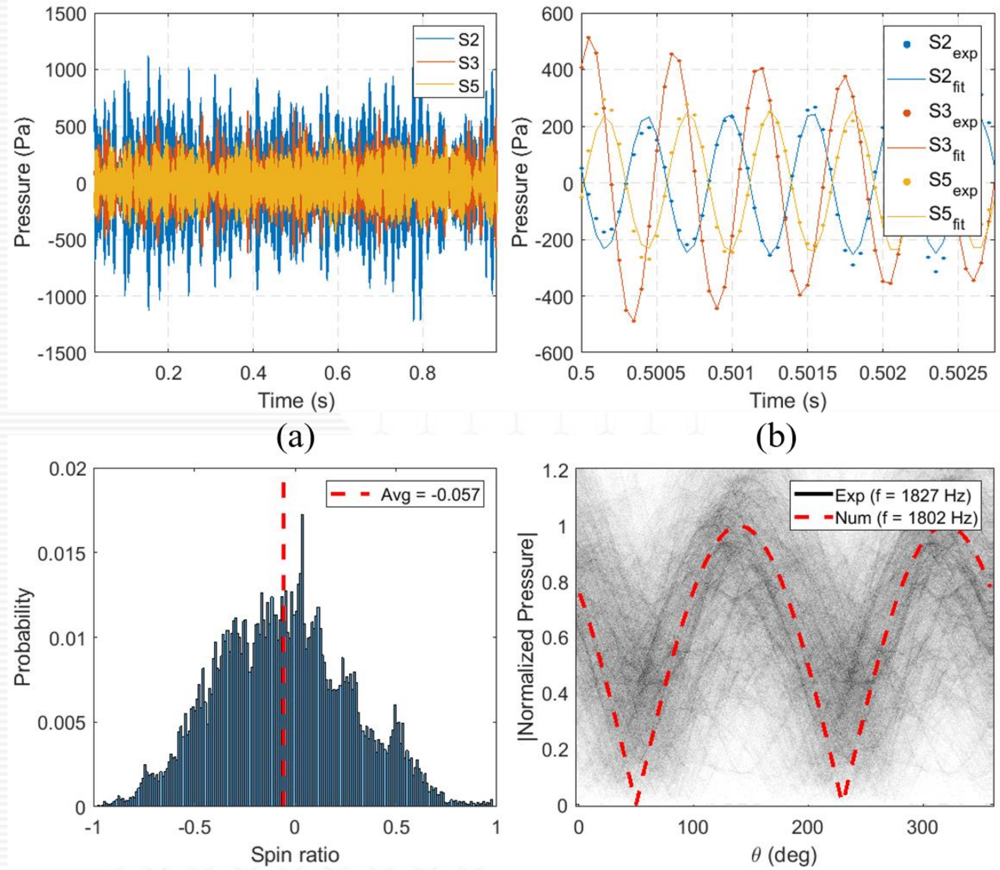

(a) (b) (c) (d)

RESEARCH TASK 3

REDUCED ORDER MODELING FOR THERMOACOUSTIC COUPLING

RESEARCH TASK 3.1 PROGRESS

IMPLICATIONS ON ANALYSIS

High-frequency => Non-compact flames

- Cannot use global heat release!
- Acoustic energy equation

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

A necessary condition for the Rayleigh Integral:

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

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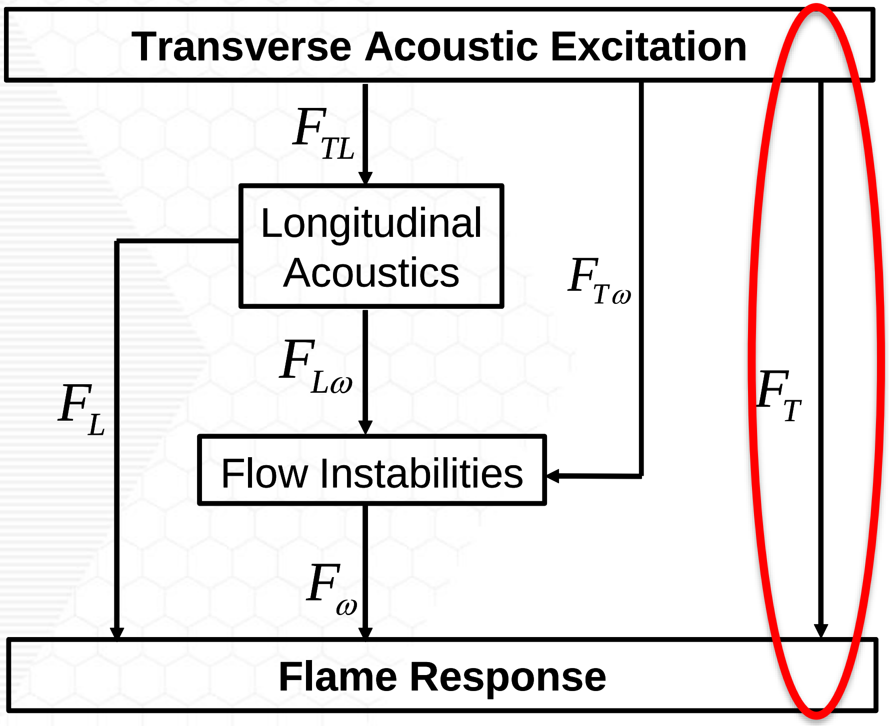
RESEARCH TASK 3.1 PROGRESS

VELOCITY COUPLED FLAME RESPONSE

Excitation mechanisms

- Direct excitation by transverse acoustic velocity disturbances F_T

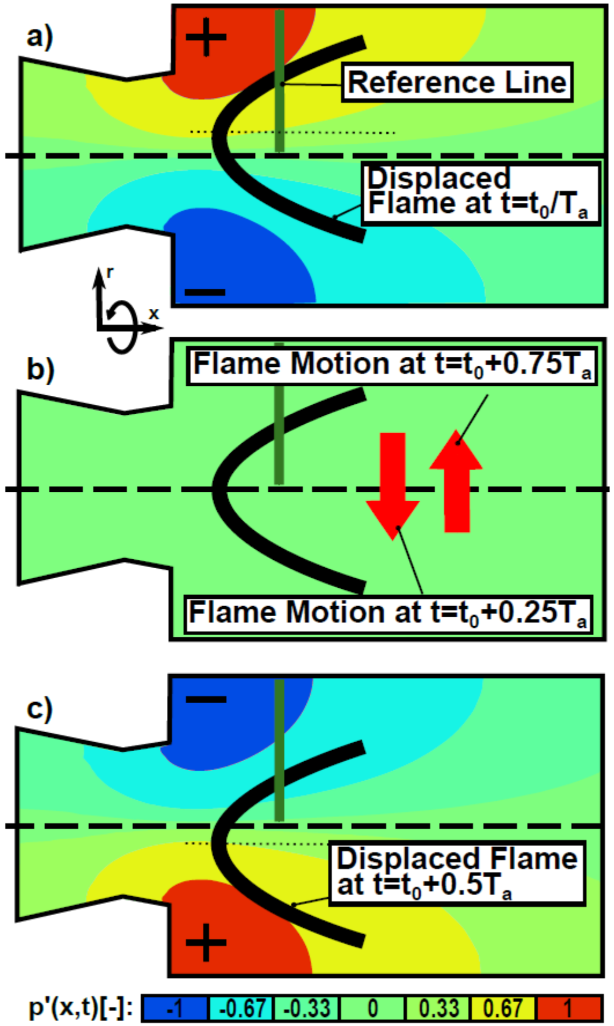


RESEARCH TASK 3.1 PROGRESS

PRIOR RESEARCH ON DIRECT EXCITATION

Sattelmayer & co-workers

- Phenomenological argument for 2D, based on flame displacement
- Modes are unconditionally unstable for thermoacoustic coupling

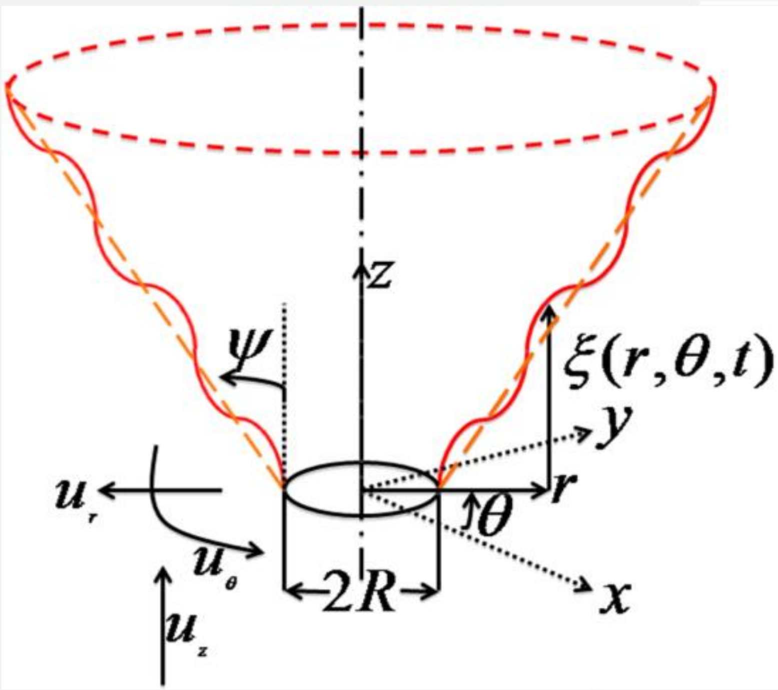


Reproduced from Hummel et al., GT2016-57500

RESEARCH TASK 3.1 PROGRESS

MATHEMATICAL FORMULATION AND FLAME MODEL

- Level-set for a thin premixed flame

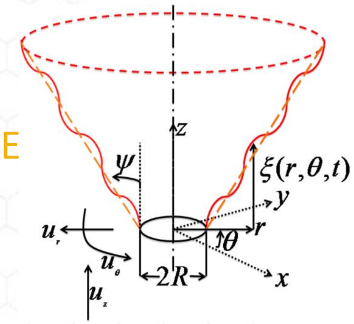


$$G(r,\theta,z,t) = z - \xi(r,\theta,t)$$

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

RESEARCH TASK 3.1 PROGRESS

MODEL PROBLEM – COMBUSTOR CENTERED FLAME



$$\left.\begin{aligned} u_{z,0} &= U_0 \\ u_{r,0} &= 0 \\ u_{\theta,0} &= \Omega r \end{aligned}\right\} \Rightarrow \xi_0(r) = \left(r - \frac{\beta_R}{\beta_f}\right)\cot\psi;\ s_L = \sin\psi$$

FOCUS: Flame response to Direct excitation by acoustic velocity disturbances only

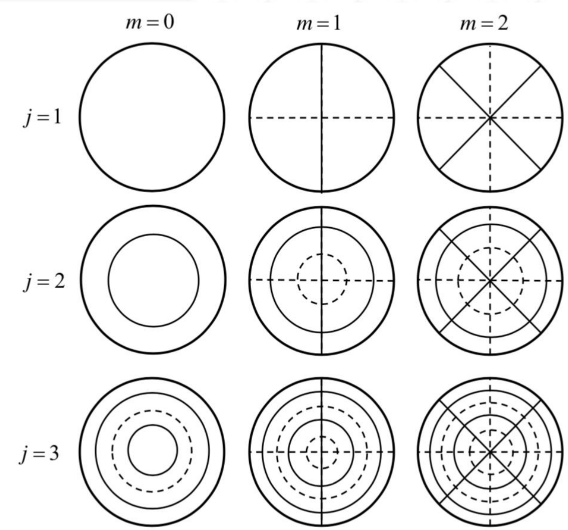
$$\hat{u}_{z,1}(r,\theta,z) = \frac{in\pi}{M_0\omega_C} J_m\left(\alpha_{j,m}\beta_f r\right)\cos\left(m\theta - \theta_m\right)\sin\left(n\pi z\frac{\beta_f}{\beta_C}\right)$$

$$\hat{u}_{r,1}(r,\theta,z) = \frac{i\alpha_{j,m}\beta_C}{2M_0\omega_C}\left[J_{m+1}\left(\alpha_{j,m}\beta_f r\right) - J_{m-1}\left(\alpha_{j,m}\beta_f r\right)\right]\cos\left(m\theta - \theta_m\right)\cos\left(n\pi z\frac{\beta_f}{\beta_C}\right)$$

$$\hat{u}_{\theta,1}(r,\theta,z) = \frac{im}{M_0\omega_C r}\left(\frac{\beta_C}{\beta_f}\right) J_m\left(\alpha_{j,m}\beta_f r\right)\sin\left(m\theta - \theta_m\right)\cos\left(n\pi z\frac{\beta_f}{\beta_C}\right)$$

$$-i\omega_0\hat{\zeta}_{1,m} + \left(\vec{u}_{0,T}\cdot\vec{\nabla}\right)\hat{\zeta}_{1,m} = \left(\hat{u}_{z,1} - \hat{u}_{r,1}\cot\psi - \cancel{\frac{\hat{u}_{\theta,1}}{r}\frac{\partial\xi_0}{\partial\theta}}\right)$$

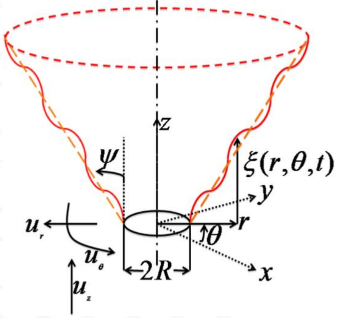
$$\hat{\dot{q}}_1 = \sum_m \frac{d\hat{\zeta}_{1,m}(r)}{dr} e^{im\theta}$$



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

RESEARCH TASK 3.1 PROGRESS

NORMALIZED RAYLEIGH INDEX



$$\hat{\dot{q}}_1 = \sum_m \frac{d\hat{\zeta}_{1,m}(r)}{dr} e^{im\theta}$$

$$\hat{p}_1(r,\theta,z) = J_m(\alpha_{l,m}\beta_f r)\cos(m\theta - \theta_m)\cos\left(n\pi z \frac{\beta_f}{\beta_C}\right)$$

$$RI = \int_t \int_V p_1 \dot{q}_1 \, dV\, dt$$

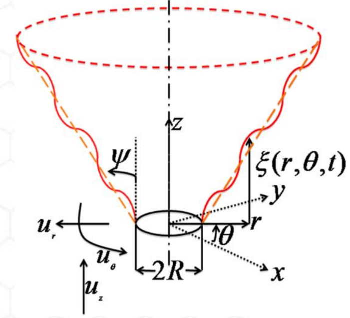
- Acoustic Energy Dynamics → Measure of growth or decay rate of energy determined by the Ratio of Rayleigh integral to the integrated acoustic energy of the mode

Normalized Rayleigh Index

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

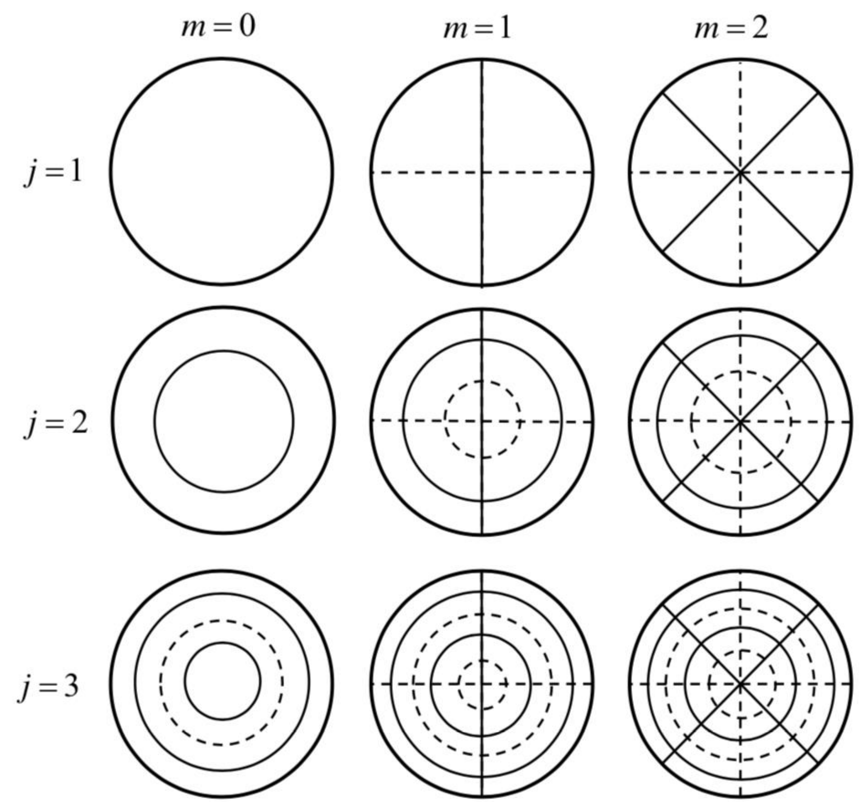
RESEARCH TASK 3.1 PROGRESS

CONTROL PARAMETERS



$$\boxed{\beta_f = \frac{L_f}{R_C} \qquad St_\Omega = \frac{\Omega L_f}{u_0}}$$

$$\boxed{\Re(\beta_f, mSt_\Omega) = \frac{RI}{2E}}$$

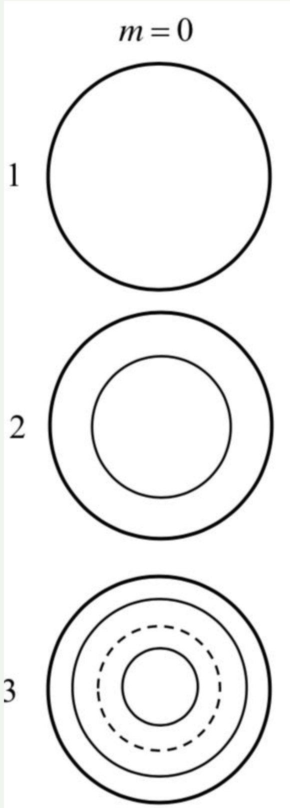


Pressure (solid) and velocity (dashed) nodal lines for several lower order transverse modes in a circular duct.

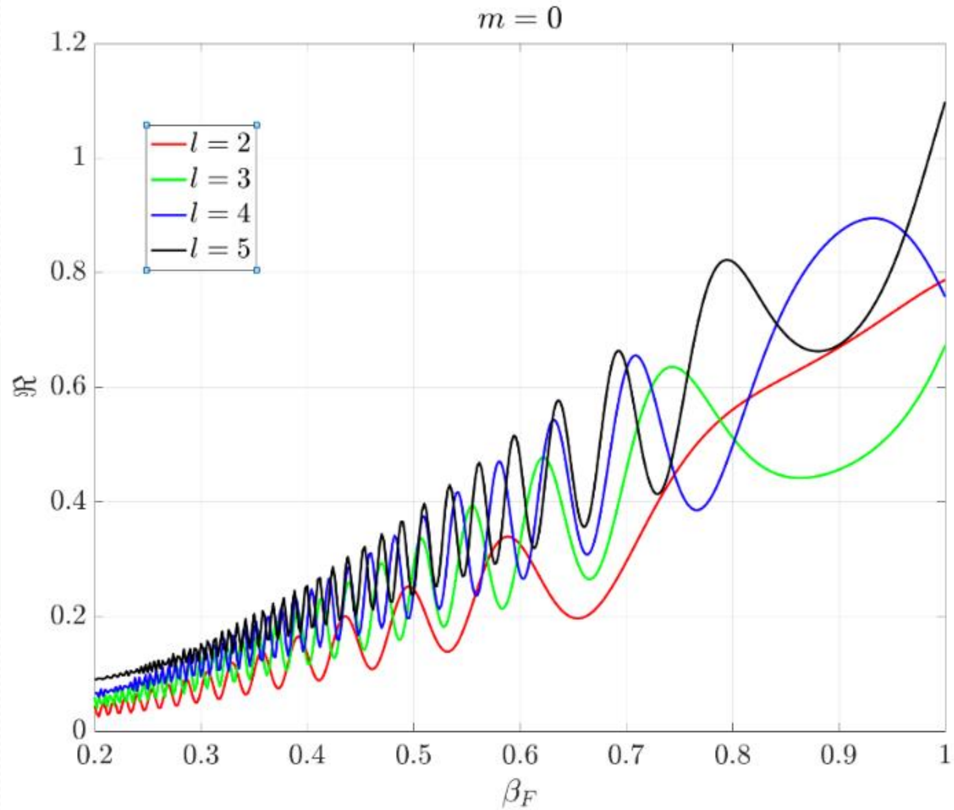
RESEARCH TASK 3.1 PROGRESS

RADIAL MODE STABILITY

$$\Re(\beta_f, mSt_\Omega) = \frac{RI}{2E}$$



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



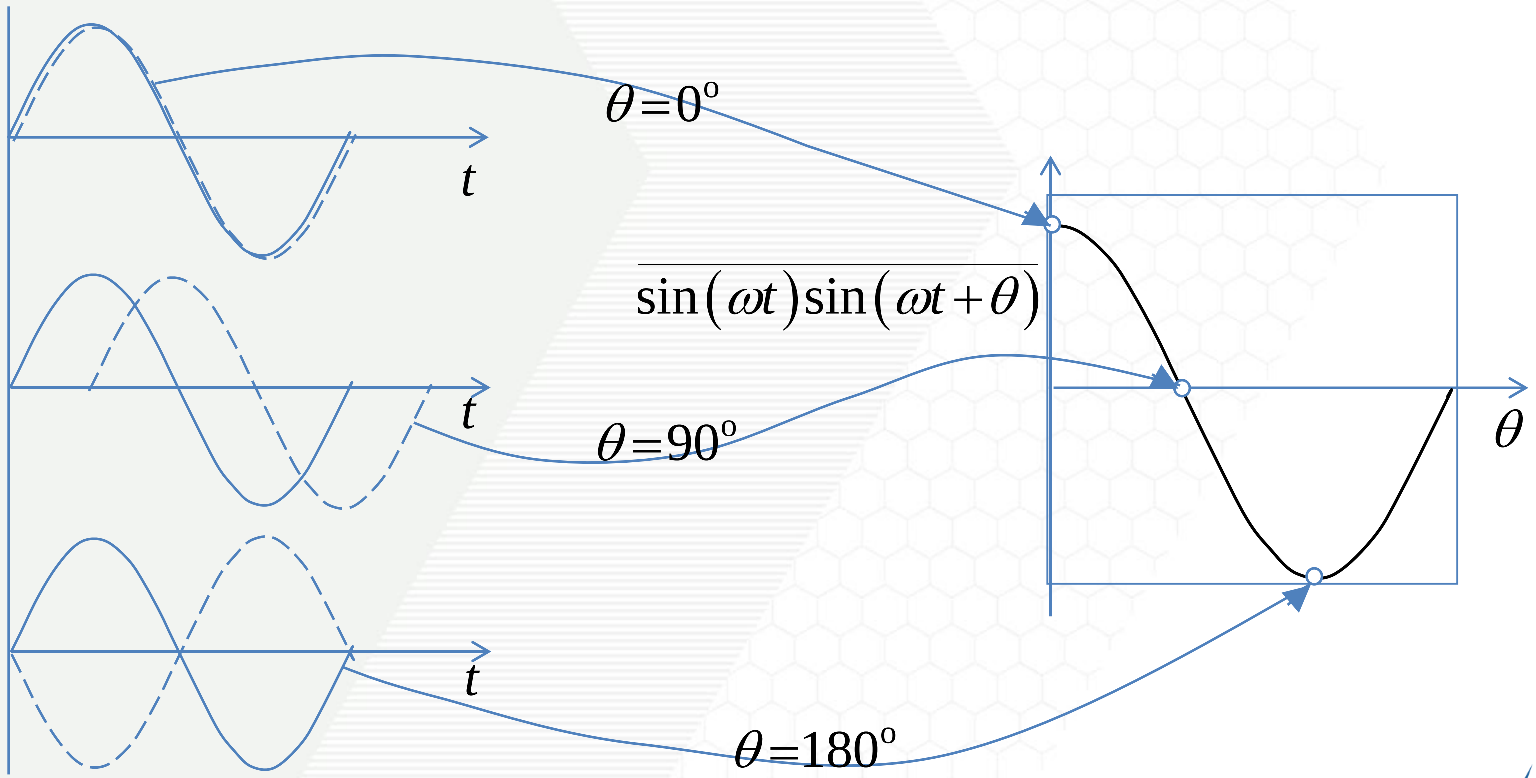
Radial-only modes are unstable in the range of operating conditions

- Consistent with prior model by Sattelmayer and co-workers

Time average of product of two fluctuating quantities depends on their relative phasing

Example

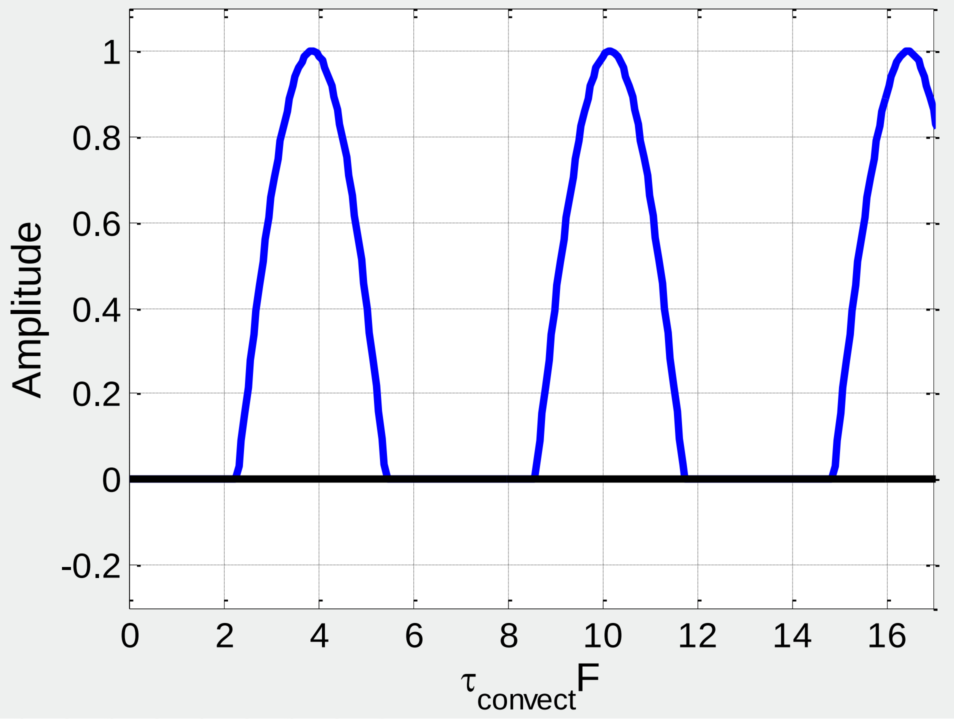
$$\overline{\sin(\omega t)\sin(\omega t+\theta)}=\frac{1}{2}\cos\theta$$



TYPICAL DEPENDENCIES - AXIAL INSTABILITIES

Instabilities can occur when:

- $\cos(t_{convect}F) > 0$
  - $t_{convect}$ = time required for mixture to convect from fuel injection point to flame
  - F= natural combustor frequency



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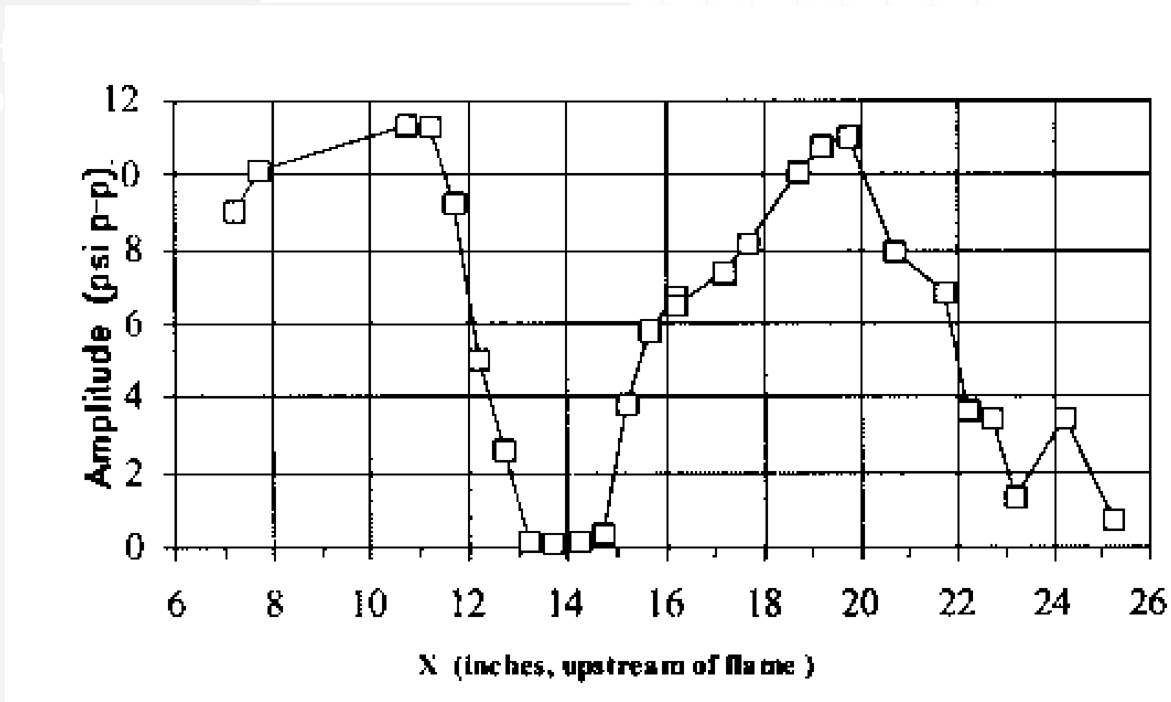
DATA ILLUSTRATING ROLE OF CONVECTIVE DELAY

PREMIXER LENGTH VARIATION

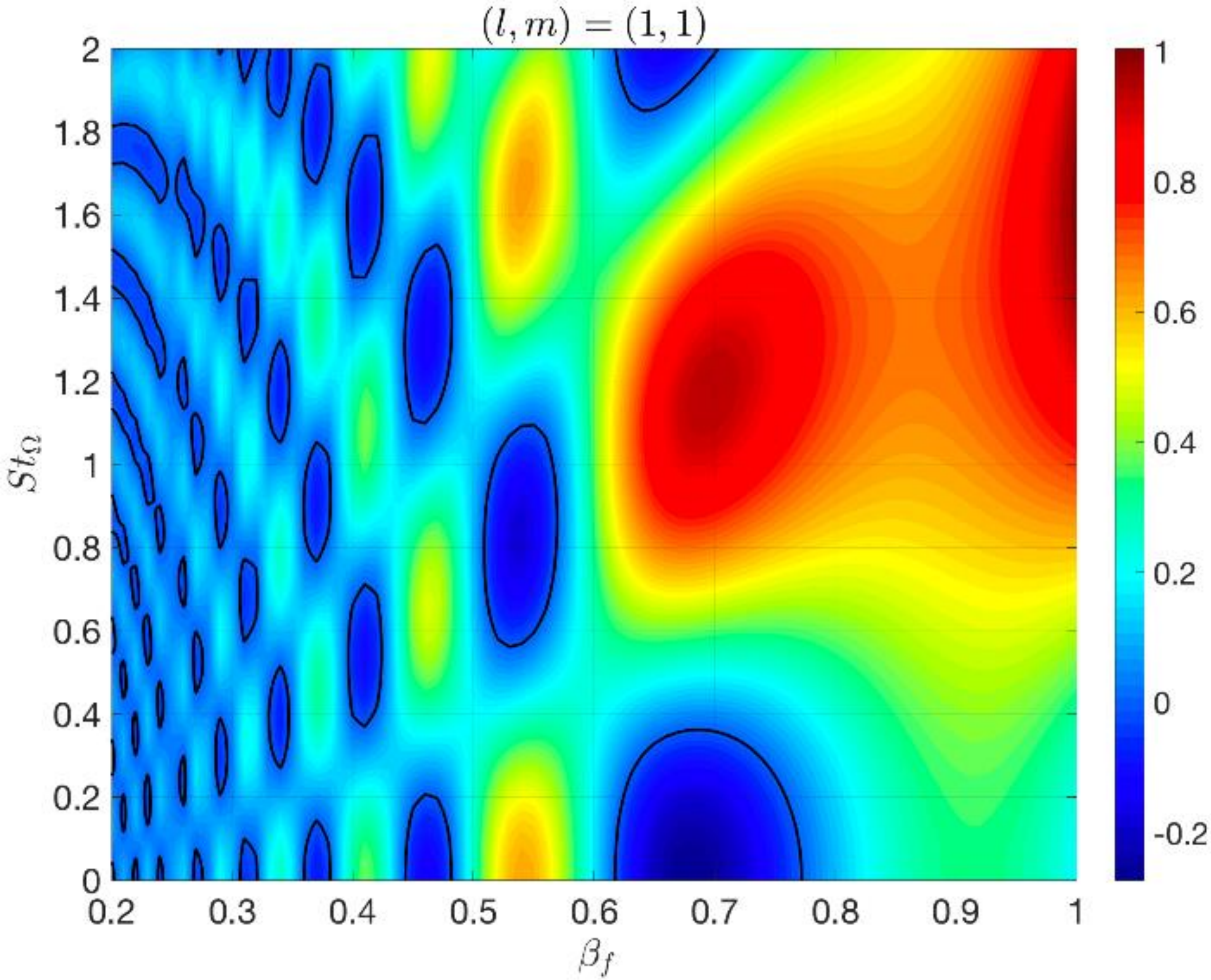
- Data shows “instability bands” of a si
- Implication:
  - “H
    co

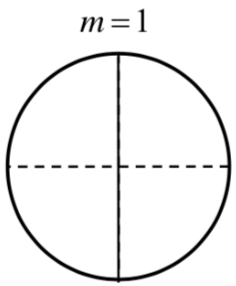


RESEARCH TASK 3.1 PROGRESS

(1,1) MODE STABILITY

$$\Re(\beta_f, mSt_\Omega) = \frac{RI}{2E}$$





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

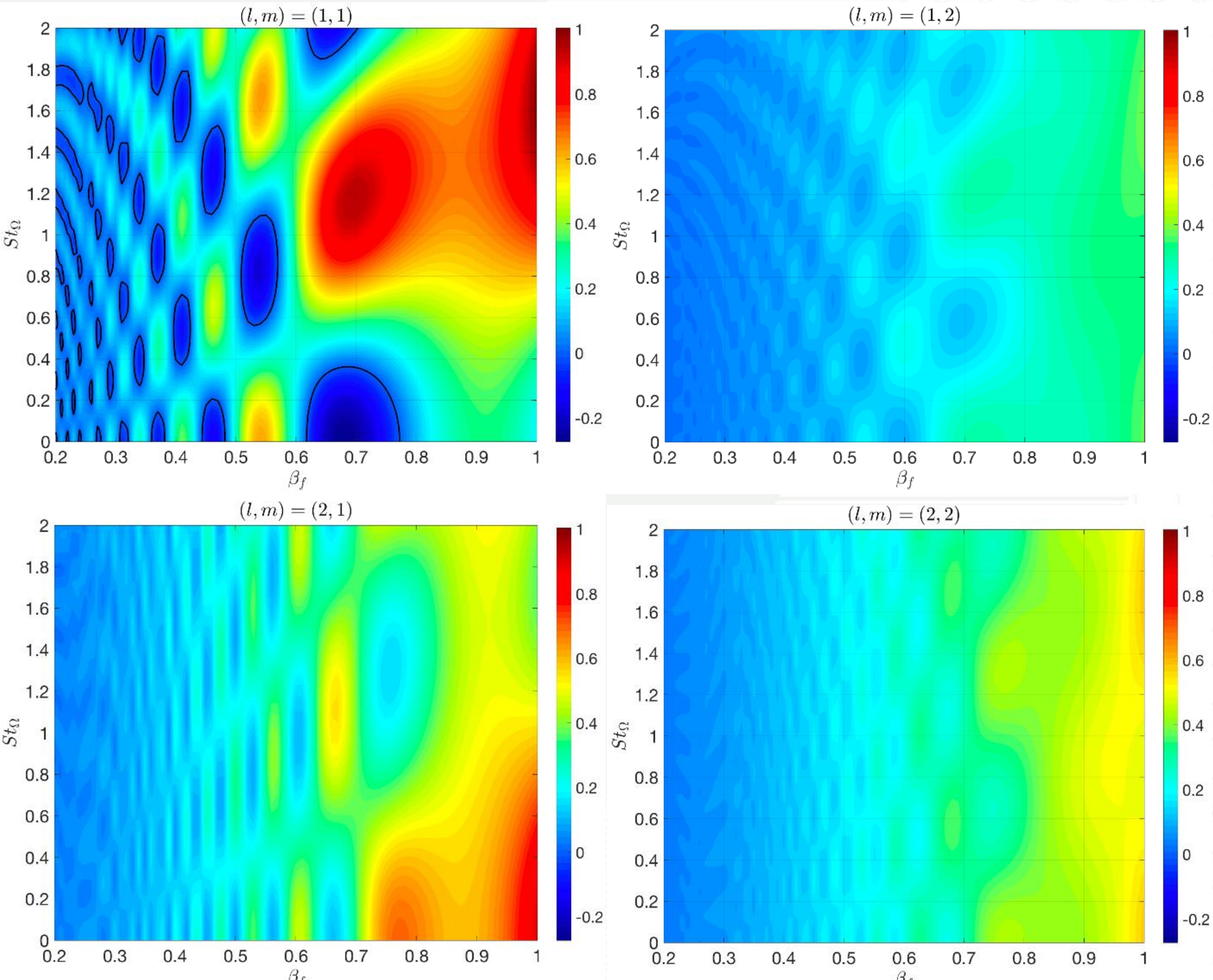
R can be positive or negative

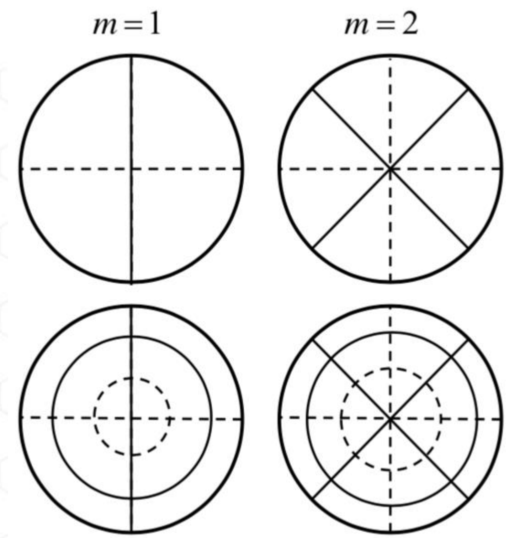
Islands of stable regions

RESEARCH TASK 3.1 PROGRESS

MIXED MODE STABILITY

$$\Re(\beta_f, mSt_\Omega) = \frac{RI}{2E}$$





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

R>0 always for other modes

(1,1) mode has the largest peak R

RESEARCH TASK 3.1 PROGRESS

TAKEAWAYS FOR CENTERED FLAME STABILITY

- Model for direct excitation mechanism of velocity coupled response of flame due to high-frequency transverse acoustic modes
  - Key difference from axial modes- unconditional instability!

- Normalized Rayleigh Index to determine mode stability.
  - Islands of negative Rayleigh index only for the (1,1) mode under the conditions investigated.
    - Highest peak R
  - (m=0); (1,2); (2,1); (2,2) modes unstable

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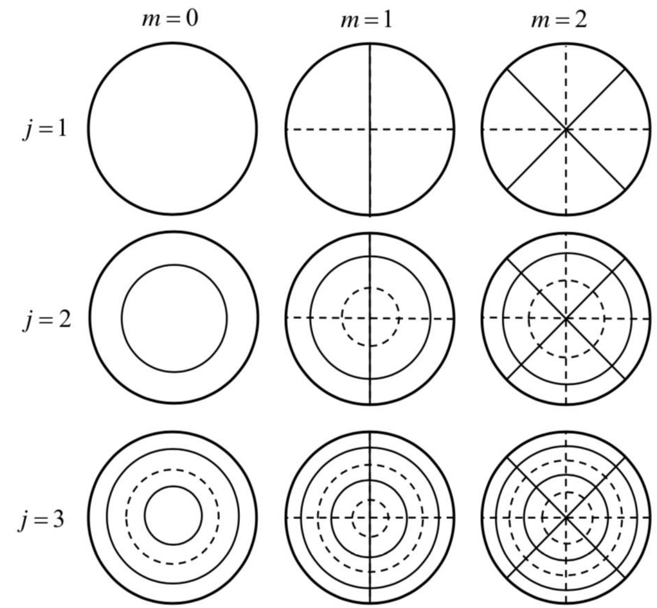
RESEARCH TASK 3.1 PROGRESS

FLAME LOCATION EFFECTS

- **Flame location relative to mode shape affects flame response and hence RI**
- **How does the mode stability change with the nozzle is offset from the combustor axis?**
- **What factors control mode stability?**



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

Reproduced from Lieuwen, Unsteady Combustor Physics, 2012

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RESEARCH TASK 3

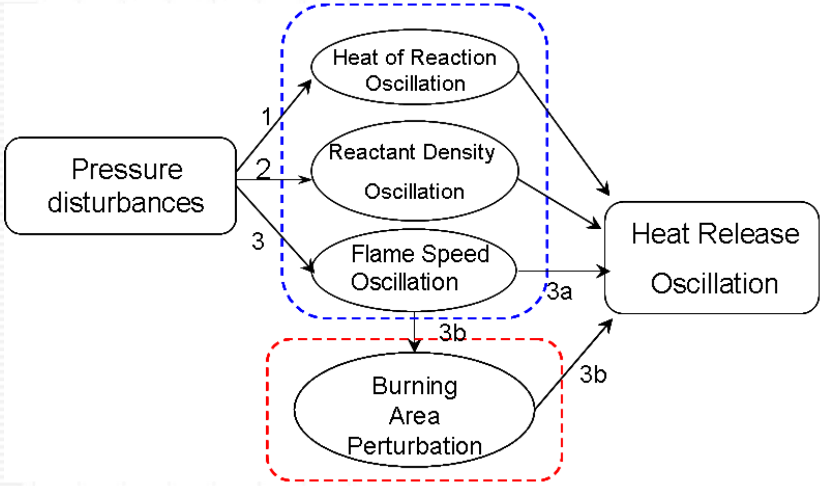
REDUCED ORDER MODELING FOR THERMOACOUSTIC COUPLING

- Subtask 2 – Hydrodynamic Stability Modeling
  - Model framework to capture inherent and acoustically excited instabilities in flow
    - Utilize optical measurements to predict fluid dynamic instabilities
    - Frequencies, growth rates, mode shapes
    - Spatial and spatio-temporal analysis
    - Predicting sensitivity to external forcing
    - ON-GOING TASK

RESEARCH TASK 3

REDUCED ORDER MODELING FOR THERMOACOUSTIC COUPLING

- <u>Subtask 3 – Kinetic Coupling Mechanism Modeling</u>
  - Task performed with supervision from COPI Wenting Sun
  - Study direct effect of pressure fluctuations on local heat release rate oscillations
  - Generalize prior single-step approach using large kinetic mechanisms
    - Initially compute using large kinetic mechanisms, then identify and use reduced-order mechanisms
  - Output: Model predicting gain and phase response of flame to input acoustic pressure perturbations



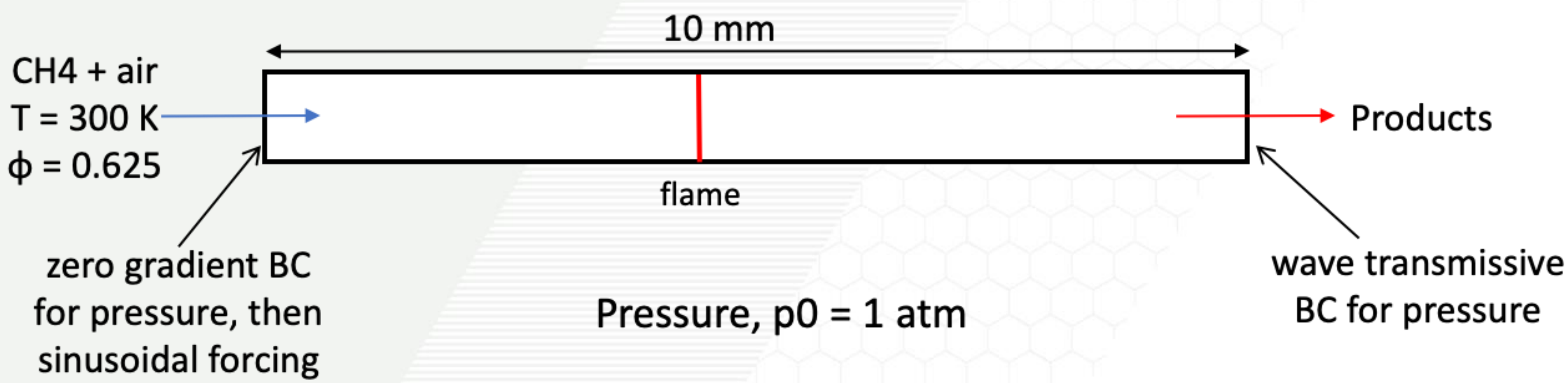
RESEARCH TASK 3

MODEL PROBLEM

- 1D laminar reacting flow simulation using OpenFOAM (ON-GOING)
  - Similar to work in literature (Jiminez et. al. & Blanquart et al.)
  - Compressible and incompressible framework
  - Domain initialized using solution from Cantera using GRI Mech 3.0 detailed chemistry for CH_4/Air.
  - After initial transients, pressure forcing is applied.

$$p = p0 + p'$$

where, $$p' = A \sin(2\pi f t)$$



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

- 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