HIGH-FREQUENCY TRANSVERSE COMBUSTION INSTABILITIES IN LOW-NOX GAS TURBINES

PI – TIMOTHY LIEUWEN
COPI – WENTING SUN

VISHAL ACHARYA,
BENJAMIN EMERSON,
DAVID WU

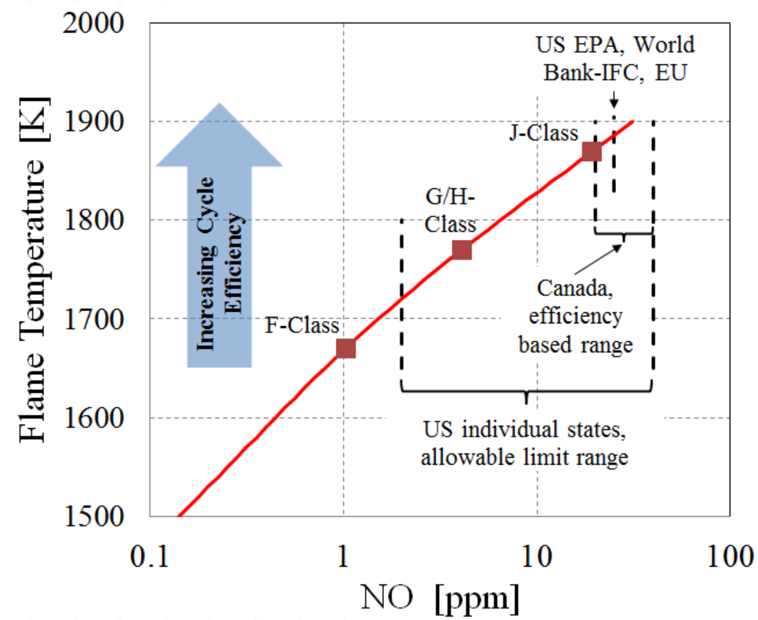
CREATING THE NEXT®

MEETING AGENDA

- Motivation for Proposed Research
- Technical background
- Proposed work
  - 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

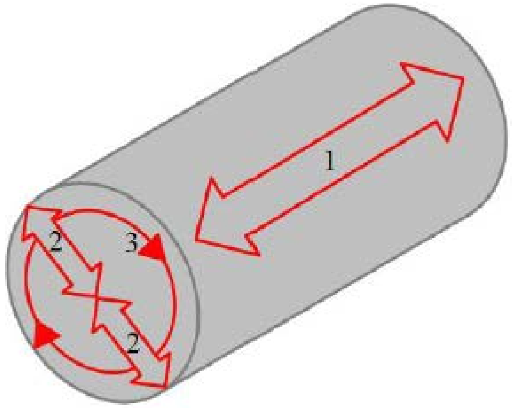
- Advances in high-temperature materials and cooling imply a push towards 65% or higher CC efficiency with low emissions → Combustion Instabilities are a challenge at this operating point
- <u>**Target architecture**</u> → Multi-nozzle can combustor configuration with interacting flames
  - Transverse modes are inherently high frequency and flames are no longer acoustically compact
  - Extensive research and literature to address longitudinal mode instabilities with acoustically compact flames
  - Motivates need for research into can combustor transverse modes with multiple interacting acoustically non-compact flames
- <u>Focus of the proposed project</u> → **High-frequency transverse combustion instabilities in multi-nozzle can combustor configurations.**

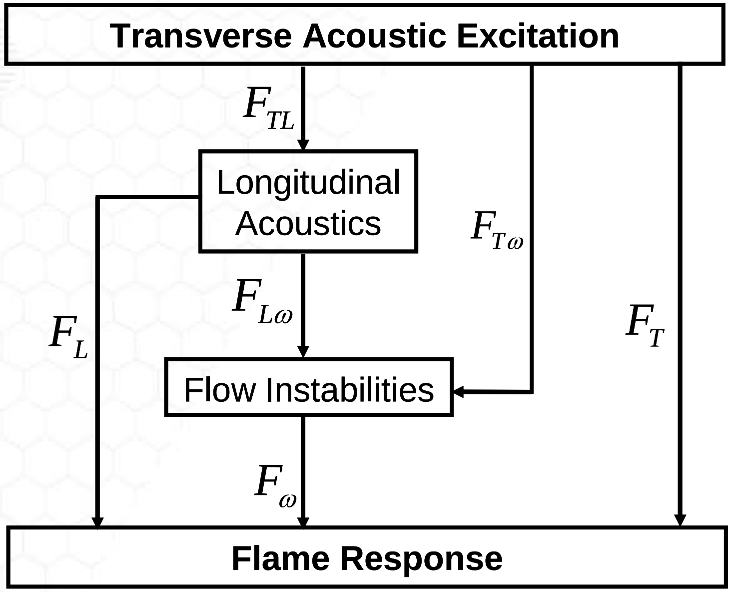


Realistic multi-nozzle experiments and high frequency modeling capabilities needed

TECHNICAL BACKGROUND
TRANSVERSE INSTABILITIES

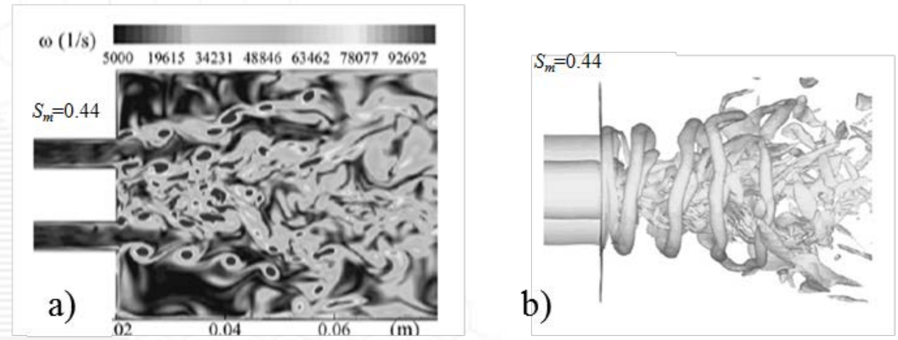
- **Combustion instability**
  - Coupling between resonant combustor acoustics and heat release rate fluctuations
  - Pressure oscillations can be detrimental to hardware lifetime and emissions.
- **Acoustics**
  - Transverse nature of instabilities implies acoustic wave motions perpendicular relative to main flow direction.
  - High-frequency implies acoustic wavelength of the order of heat release zone extent.
  - Acoustics excites flame through various pathways
    - Transverse modes create multi-dimensional longitudinal acoustics at nozzle junctures

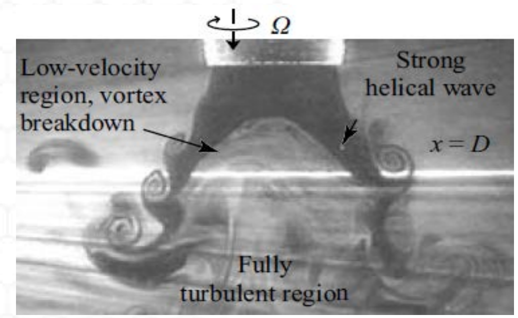


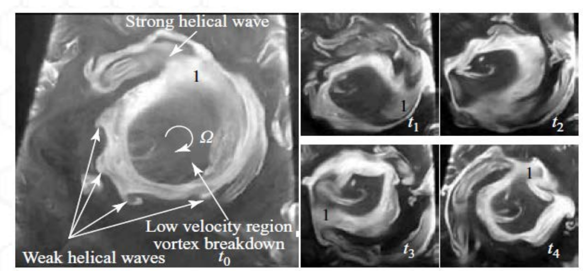


TECHNICAL BACKGROUND HYDRODYNAMIC INSTABILITIES

- Acoustics excites dynamical flow structures
  - Complex swirling flow features such as PVC interact with acoustics
- Hydrodynamic stability analysis can calculate most sensitive frequencies and excitation shapes
- Temporal vs. Spatial stability analysis
  - Temporal: Calculates growth of absolutely unstable modes
  - Spatial: Calculates growth of convectively unstable modes
- Convective vs. Absolute instability
  - Convective: amplitude grows in space
  - Absolute: amplitude grows in time



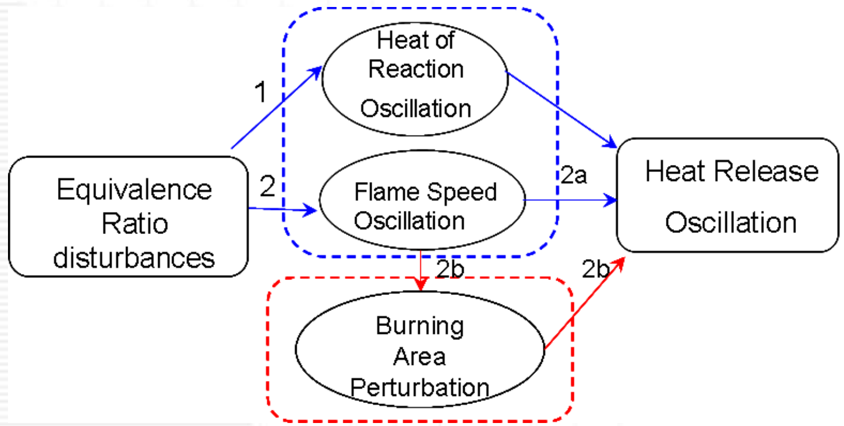


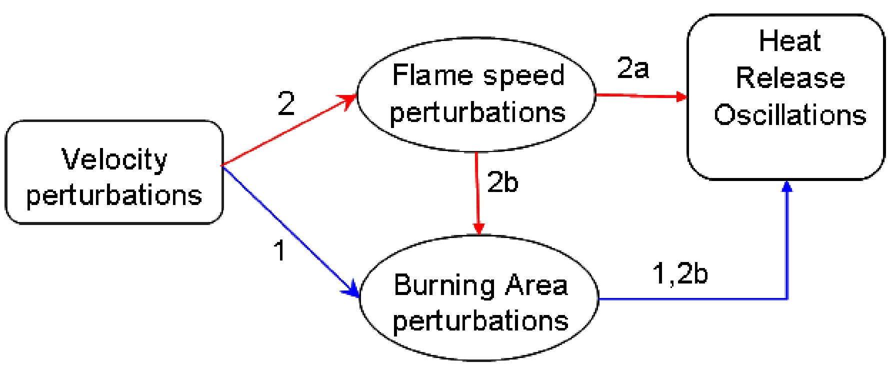


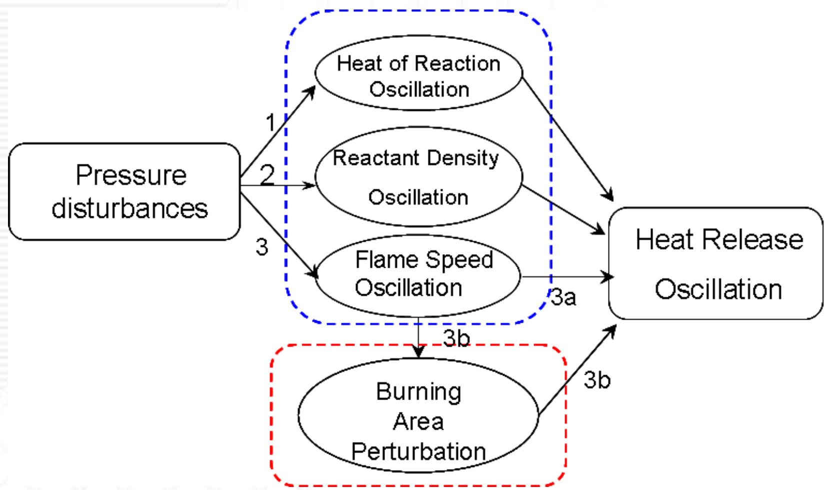
BEN T. ZINN COMBUSTION LAB

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

- Understanding high-frequency transverse instabilities in gas turbines.
  - Combined use of experiments and reduced-order modeling

- **Key research questions**:

(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

TASK 1
PROJECT MANAGEMENT AND PLANNING

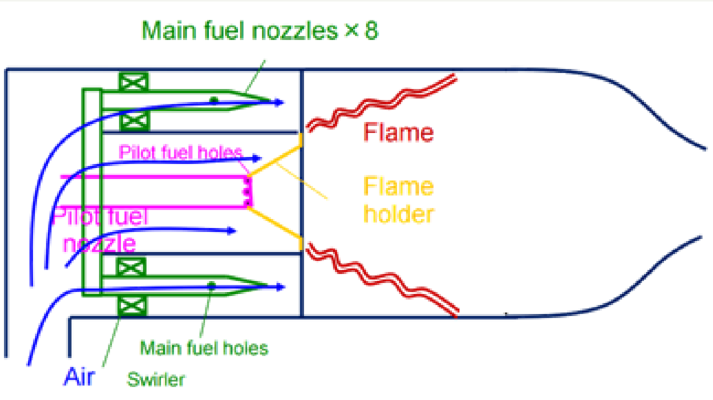
- Overall project management and progress managed by PI Tim Lieuwen

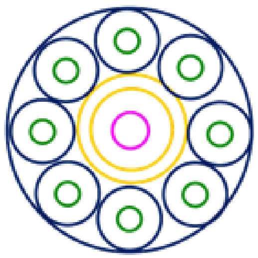
- Project management plan (PMP)
  - Updated directly following award & every alternate quarter
  - Key risk management tool
    - Outlines technical, financial, and schedule driven program risks
      - Highlight risk level at time of PMP update
      - Include action plan for reduction or rational for acceptance
  - Tracks milestones/critical decision points
    - Ex: Down-select of experimental concepts

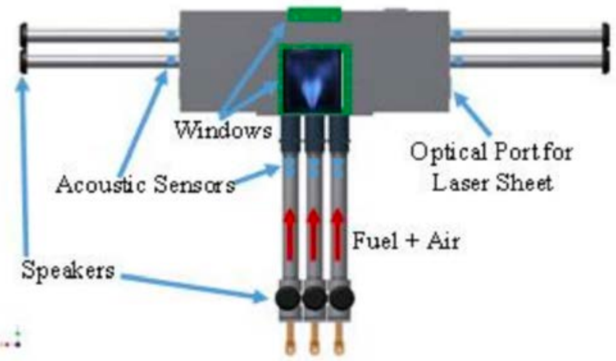
RESEARCH TASK 2

DESIGN OF EXPERIMENT FOR SELF-EXCITED TRANSVERSE INSTABILITIES

- Task team will be led by the PI Prof. Lieuwen and include Research Engineers Ben Emerson and David Wu
- <u>Task 2.1: Design of experiment</u>
  - Design realistic multi-nozzle can combustor with optical access
  - Test facility for self-excited acoustics
    - Test for self-excited modes at atmospheric pressure
    - If failure at atmospheric, test at high pressure
    - Poor data quality → utilize existing externally forced combustor







RESEARCH TASK 2

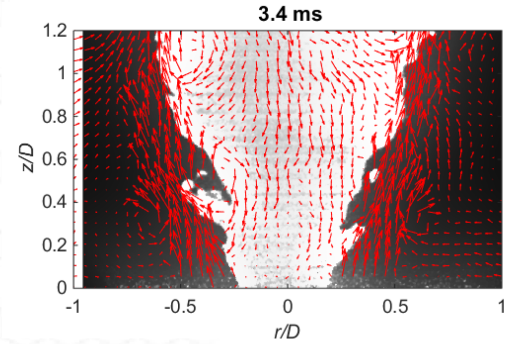
DESIGN OF EXPERIMENT FOR SELF-EXCITED TRANSVERSE INSTABILITIES

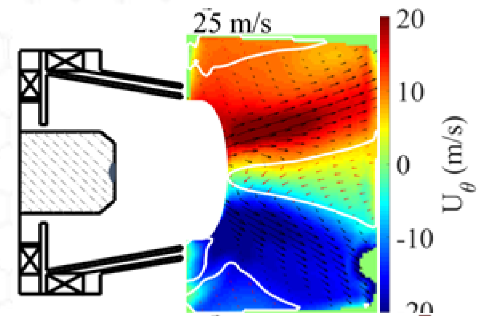
<u>Task 2.2: Spatio-temporal characterization of unsteady pressure</u>

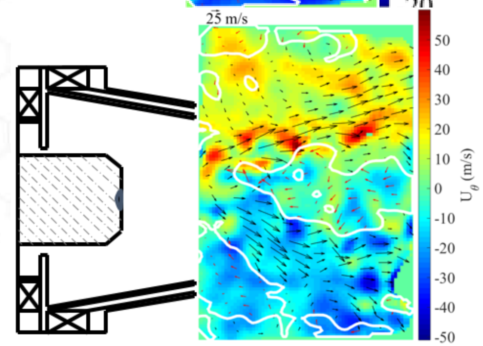
- Identify the acoustic modes in the experiment
- FEM for acoustic modes
  - Identifies necessary number and location of acoustic sensors
  - Helps differentiate between modes with similar frequencies i.e. Spinning vs. standing or transverse vs. longitudinal

<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
- Identify key physics driving the instability
  - Fluid-dynamic to acoustic coupling or feed system coupling to acoustics
- Generate quantitative data to refine and validate the model(s)







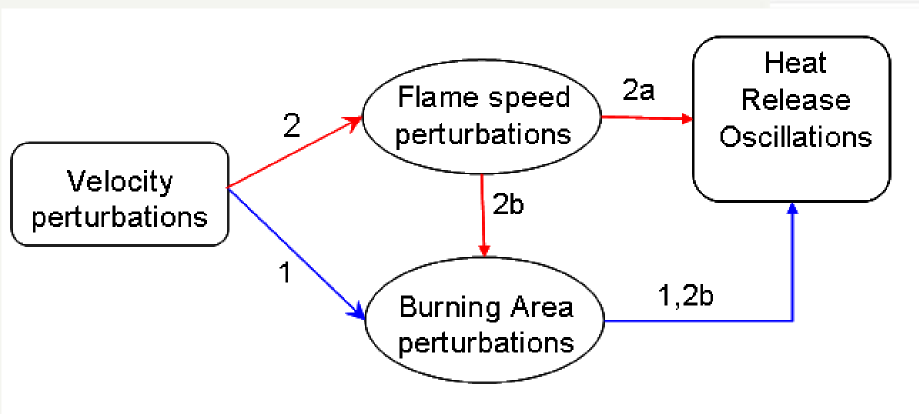
RESEARCH TASK 3

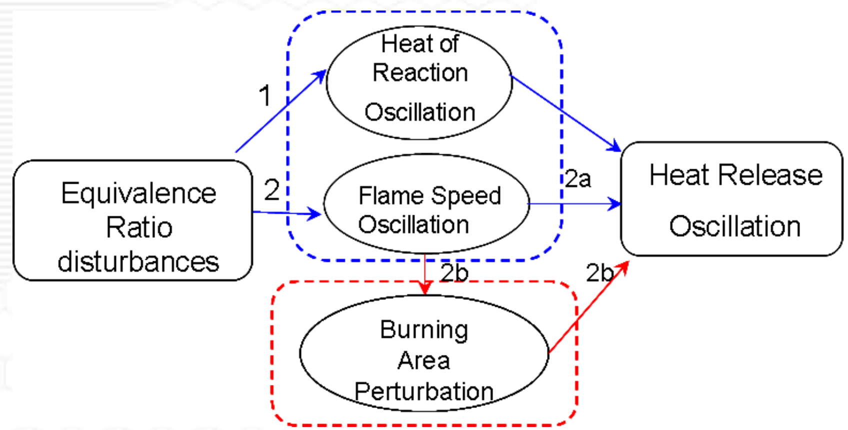
REDUCED ORDER MODELING FOR THERMOACOUSTIC COUPLING

- This task is broken into sub-tasks and is led by the PI Tim Lieuwen
- <u>Subtask 1 – Flame Response Modeling</u>
  - Task performed with supervision from Research Engineer Vishal Acharya
  - Using Phenomenological description of flame to capture response to velocity and equivalence ratio fluctuations

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

Connects to Subtask 2 and 3





Georgia Tech
BEN T. ZINN COMBUSTION LAB

RESEARCH TASK 3

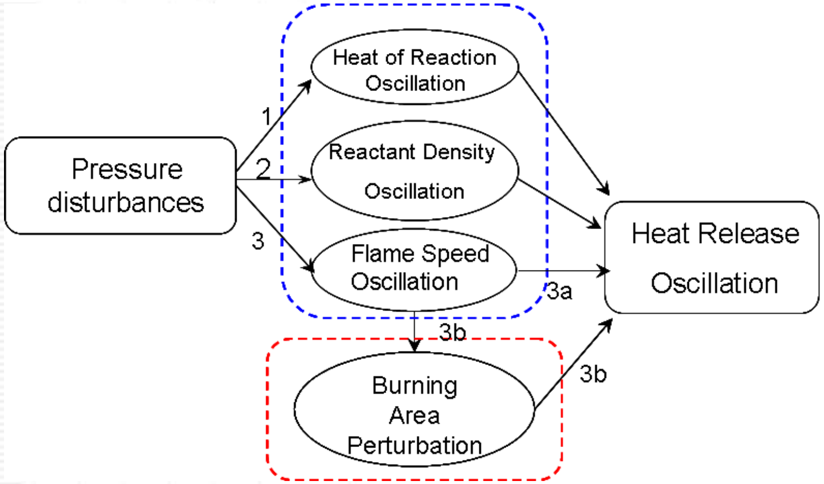
REDUCED ORDER MODELING FOR THERMOACOUSTIC COUPLING

- Subtask 2 – Hydrodynamic Stability Modeling
  - Task performed with supervision from Research Engineer Ben Emerson
  - 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

RESEARCH TASK 3

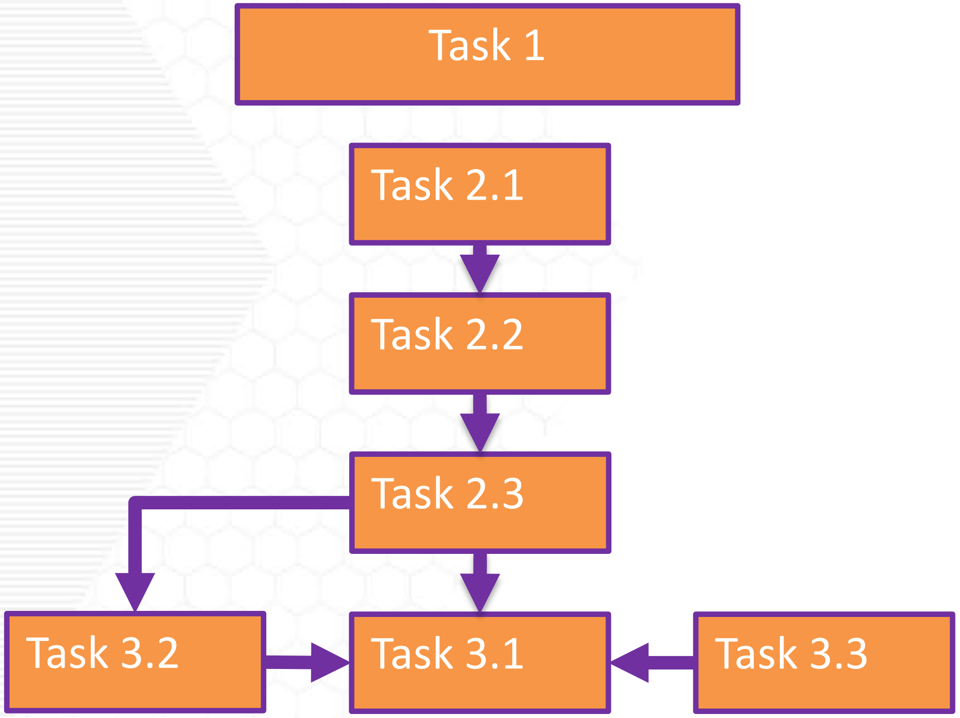
REDUCED ORDER MODELING FOR THERMOACOUSTIC COUPLING

- <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



TASK 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



SCHEDULE OF DELIVERABLES

Deliverables	Quarter											
	1	2	3	4	5	6	7	8	9	10	11	12
Task 1 – Revised PMP	●											
Task 1 – Updated PMP			●		●		●		●		●	
Task 1 – Update DMP	●			●				●				●
Task 2.1 – Experiments for Self-Excited Transverse Instability				●								
Task 2.2 – Unsteady Pressure and Mode Shape Characterization								●				●
Task 2.3 – Optical Diagnostic Measurements								●				●
Task 3.1 – Flame Response Modeling				●								
Task 3.2 – Hydrodynamic Stability Modeling				●				●				●
Task 3.3 – Kinetic Coupling Mechanism Modeling							●					●
Reporting	1	2	3	4	5	6	7	8	9	10	11	12
Quarterly Progress Reports	●	●	●	●	●	●	●	●	●	●	●	●
Semi-Annual Reports		●		●		●		●		●		●
Annual Reports				●				●				●
Final Report												●