Combustion and Combustion Instabilities in Gas Turbines and Rockets
Introduction and Motivation

The problem of CI’s is two-fold depending on acoustics and combustion.
- Requires understanding of the acoustic response of engine components and dynamic flame response.

Combination of Acoustic and Combustion Experiments and Modeling Efforts
Research interests

- Acoustic response measurements of gas turbine and rocket engine components
- Liquid, and hybrid rocket combustion: Flow, spray, and flame response to acoustic oscillations
- Solid rocket motor combustion instabilities
- Gas turbine engine combustion: Flame response to acoustic pressure and velocity and fuel-air ratio oscillations
- Reduced-order thermo-acoustic network modeling and tool-development
- Combustion processes in wild land fires
- Design tool development
  - Design combustion systems with combustion instabilities in mind
  - Ability to come up with ‘fixes’ quickly and cost-effectively
- Application of machine learning to combustion related issues
Optimal Design for Stability
Sense-port Acoustic Response Measurements

- Investigate the acoustic response of various sense-port geometries using the MMM for high-accuracy measurements
- Multiple spacings yield high-accuracy measurements in a broad frequency range
**Acoustic Sense Port Response**

- Measuring the pressure at the end (sensor 2) and the entrance (sensor 1) of the sense port.

- Calculating the parameters of interest
  - Ratio of the amplitude of the power spectrum amplitude at sensor 2 to sensor 1
  - Difference in the phase angle of the power spectrum at sensor 2 to sensor 1
Orifice Acoustic Response Measurements

Impedance
Impedance measured at $\frac{1}{4}$ wave resonance of each orifice

Orifice Impedance
- Slope increases as $\sigma$ increases
- Nonlinearities decrease as $\sigma \to 1$
Low Frequency Control Volume Analysis

- Control volume analysis (CVA) of acoustic wave propagation in a rectangular combustor
  - mean flow conditions while the wave equation method is inseparable
  - Impedance wall boundary conditions
- Low frequency solution valid below cutoff
- Suitable for use in reduced order models

\[
\frac{\partial^2 p'}{\partial t^2} + \left(v_{z,o}^2 - a_0^2\right) \left(\frac{\partial^2 p'}{\partial z^2}\right) + 2 v_{z,o} \left(\frac{\partial p'}{\partial z}\right) + \left(a_0^2 \xi + \frac{\xi_o}{\rho_o}\right) \left(\frac{\partial p'}{\partial t}\right) + \left(a_0^2 \xi v_{z,o} + \frac{\xi_o}{\rho_o} v_{z,o}\right) \left(\frac{\partial p'}{\partial z}\right) + a_0^2 \xi_o \xi p' = 0
\]

\[
\xi = \frac{\rho_o}{L} \left[\left(\frac{1}{Z_{W}^{x=L}} + \frac{1}{Z_{W}^{x=0}}\right) + \frac{1}{\rho_o a_0^2} \left((v_o)^{x=L}_{W} - (v_o)^{x=0}_{W}\right)\right] + \frac{\rho_o}{H} \left[\left(\frac{1}{Z_{W}^{y=H}} + \frac{1}{Z_{W}^{y=0}}\right) + \frac{1}{\rho_o a_0^2} \left((v_o)^{y=H}_{W} - (v_o)^{y=0}_{W}\right)\right]
\]

\[
\xi_o = \frac{1}{L} \left[(\rho_o v_o)^{x=L}_{W} - (\rho_o v_o)^{x=0}_{W}\right] + \frac{1}{H} \left[(\rho_o v_o)^{y=H}_{W} - (\rho_o v_o)^{y=0}_{W}\right]
\]
Nonlinear Area Contraction Acoustic Response Model

Nonlinear model for acoustic response of area changes using Fourier Series

After breaking down the oscillating pressure and velocity as Fourier series, we can represent the pressure and impedance as a function of the fundamental and acoustic velocity, and \( \alpha \) terms which are functions of the area ratio

\[
(p_{1,0} - p_{2,0}) = \left| u_{1,1} \right|^2 \left\{ \frac{\alpha_f}{\omega T} (2\pi - 2\theta) + \frac{\alpha_r}{\omega T} (2\theta) \right\} \left( \frac{u_0}{u_{1,1}} \right)^2 + \cdots
\]

\[
\left\{ \frac{\alpha_f}{\omega T} (\pi - \theta) - \frac{\sin(2\theta)}{2} + \frac{\alpha_r}{\omega T} \left( \theta + \frac{\sin(2\theta)}{2} \right) \right\}
\]

\[
Z = \left( \frac{\rho c}{S} \right)_{1} \left( \frac{u_{1,1}}{\rho c} \right)_{1} \left( \frac{u_0}{u_{1,1}} \right)^2 \left\{ \frac{\alpha_f}{\omega T} \left( \pi - \theta - \frac{\sin(2\theta)}{2} \right) + \frac{\alpha_r}{\omega T} \left( \theta + \frac{\sin(2\theta)}{2} \right) \right\} + \cdots
\]

\[
- i \frac{\rho_0 L_c}{S_1} \left( \frac{u_0}{u_{1,1}} \right)^2 \sin(\theta) + \frac{1}{3} \left[ 9 \sin(\theta) + \sin(3\theta) \right]
\]
Acoustic Response of Burning Propellant

- Identify acoustic response of sense-lines at realistic engine conditions.
  - Elevated-pressures and temperatures.
  - Reacting flows (liquids, solids, both).
- Apply this knowledge to rocket tests.
Oxy-fuel combustion

- Research goals:
  - Investigate oxygen-methane combustion
  - Characterize swirled injectors to acoustically forced combustion
  - Identify fundamental mechanism behind using baffles for reducing combustion instabilities

- Water cooled, optically accessible combustion chamber capable of 100 psi acoustically forced combustion

- Modular speaker housing / injectorhead
  - Allows for longitudinal / transverse forcing

- CH* Chemiluminescence used for burnout length measurements

- High speed chemiluminescence techniques used for heat-release transfer function measurements
Energy Recovery and Conversion

- In-situ steam generation for enhanced oil recovery
- Injector development for stable oxy-methane combustion system
  - Combustion stability in submerged conditions
  - Low emissions and stability
  - Oxy-fuel for no-NOx
Solid Propellant Burning Rate Experiments

- Optically measure the burning rate response of different solid and hybrid propellants of solid rocket propellant’s reactions to acoustic pressure and velocity oscillations
- Quartz tube for optical diagnostics
- Port for a dynamic pressure transducer
- Up to four speakers for acoustic forcing
- Gas flow system with variable area orifice exhaust
Thrust Stand

- Initially validate rig and instrumentation using commercially available SRMs
- Test different formulations and configurations of solid rocket propellant and observe any acoustic instabilities
- Determine valuable instrumentation for large scale SRMs
- Excite acoustic fields into SRMs and observe effects
- Dynamic and absolute pressure transducer in forward bulkhead
- Strain gauges on the outside of case
- Fiber-optic coupled PMT (photo-multiplier tube) in forward bulkhead
- Exhaust temperature measurement
- External case temperature
Hybrid Rocket Combustion

- Investigate combustion instabilities and regression rates in hybrids for both HTPB and paraffin through the following experiments
  - Characterization of hybrid acoustics under cold conditions
  - Hot fire test experiments
  - Development of a optically accessible 2D slab burner
  - Acoustic field propellant sample burn testing

- Hybrid is capable of 100 lbs of thrust and operates at about 100 psi
- Test stand can mount the hybrid horizontally or vertically and is capable of withstanding over 2,000 lbs of thrust allowing for compatibility with future designs
Equivalence Ratio Oscillations Effects

- Study the effects of equivalence ratio oscillations on combustion instabilities
- Observe equivalence ratio oscillations with Helium-Neon laser on modified Bunsen burner; then use developed test equipment to observe equivalence ratio oscillations on Swirl Combustor
- Hydrocarbon Absorption
  - Certain hydrocarbons absorb light around 3390 nm
  - Helium-Neon lasers can emit light at this wavelength
  - Beer-Lambert Law can give concentration based on this
- Beer-Lambert Law
  \[
  \frac{I}{I_0} = \exp(-\alpha \cdot L \cdot P \cdot x_i)
  \]
Thermo-acoustic Instability Modeling

Mode shape predictions for sample combustion system (Model)

Frequency (Hz) vs Combustor Length (in)

Frequency (Hz) vs Combustor Length (in) (Experiment)
Augmentor Acoustic Modeling

- Experimental points from tests: 071106_01_T40 (Ap-p_{MAX} = 30%), 071406_01_T41 (Ap-p_{MAX} = 34%)
- P, V curves calculated for M = 0.35, Tin = 1000K, Tout = 2000K
An Experimental and Numerical Study of the Environmental and Combustion Characteristics of Wildland Fuels
Project Overview

- Experimental and Numerical study of the propagation of wildland fires, particularly in the Southeast United States
- Develop a three-dimensional, physics based, time accurate model for simulating the spread of forest fires in the Southeast United States

**Experimental test rig:**
- Glass side walls create a quasi-2D condition and allow us to use cameras for thermal imaging, high speed video, and flame geometry detection
- Weight table mounted on load cells to measure mass consumption

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Measurement Device</th>
<th>Reason</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature profile</td>
<td>Thermocouples</td>
<td>Determine heat spread ahead of fire</td>
</tr>
<tr>
<td>Mass consumption rate</td>
<td>Load Cells</td>
<td>Determine how fast the fuel is being pyrolyzed and combusted</td>
</tr>
<tr>
<td>Combustion products</td>
<td>Gas analyzer</td>
<td>Provides information on the reactions and species involved in the combustion process. Pollution impact.</td>
</tr>
<tr>
<td>Video footage</td>
<td>Camera</td>
<td>Re-watch the experiment as many times as needed</td>
</tr>
<tr>
<td>Still images</td>
<td>Camera</td>
<td>Determine flame geometry</td>
</tr>
</tbody>
</table>
Fire Dynamics Simulator (FDS) Simulations

Fire strip simulation just after ignition

Temperature slice and temperature of pine straw particles