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14. ABSTRACT
An experimental study has been conducted at the Air Force Research Laboratory(AFRL) at Edwards Air Force Base to explore the coupling between a coaxial jet flame and transverse acoustic perturbations. A new experimental facility at AFRL was used to expose a single H_2/O_2 shear coaxial diffusion flame to controlled acoustic resonances. A variety of chamber conditions including acoustic resonance properties were considered. The acoustic frequency and amplitude were selected relative to the characteristic frequency and dynamic pressure of the reacting injector flow. Placing the flame within the pressure node and antinode was also considered. Diagnostics employed high-speed imaging including backlit visualization and OH* chemiluminescence. The images were analyzed using proper orthogonal decomposition to identify the natural frequencies and organized structure of the unforced jet flame. These techniques were used to elucidate the effects of forcing, including the structure and relative importance of forced modes relative to the natural flame behavior.

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The Response of Cryogenic H2/O2 Coaxial Jet Flames to Acoustic Disturbances

AIAA SciTech 2015

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Integrity ★ Service ★ Excellence

Outline

- **Background and objectives**
- **Experimental facility**
  - Overview of features
  - Current operating conditions
- **Unforced characteristics**
  - With and without flame
  - Spectral features
- **Forced flame results**
  - With and without flame
  - Pressure node and antinode
  - Dynamic mode decomposition analysis
- **Conclusions and future work**

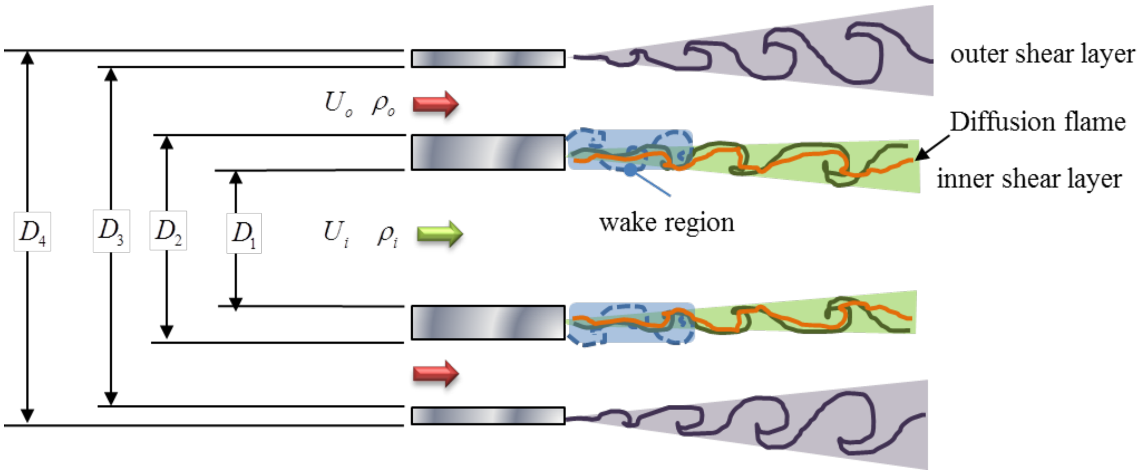
Background

- **Combustion systems can no longer be designed to meet modern requirements without considering system dynamics**
- **Combustion dynamics always includes acoustic waves, and in enclosed systems, acoustic waves can often reach detrimental amplitudes**
  - **eg, combustion instabilities**
- **Achieving modern thermodynamic efficiencies requires achieving increasingly higher chamber pressures, sometimes exceeding the critical pressure of the reactants**
  - **eg, liquid rockets, future gas turbines**
- **When the combustion systems are for propulsion, limited tankage dictates that on-board propellants be stored in condensed form**
  - **eg, kerosene, liquid oxygen in rockets**

Objectives

- **Accordingly, we consider here the dynamics of a high pressure, chemically reacting, multiphase, acoustically driven shear flow in the form of a coaxial jet flame**
  - **Canonical flow**
  - **Geometry is applicable to liquid rockets**
  - **Subcritical and supercritical pressures**
  - **With and without acoustic waves at various amplitudes**
  - **Traceable to past research on non-chemically reacting coaxial jets**
  - **Liquid oxygen and gaseous hydrogen, also applicable to liquid rockets**
    - **Future: kerosene**
- ***Objectives***
  - **Effect of variations in the above quantities; regime maps**
  - **Effect of the presence of chemical reactions; comparison between cold and hot**
  - **Effect of the presence of neighboring coaxial jet flames**

Coaxial Jets/Flames



Geometry parameters

Area ratio

$$AR = \frac{D_3^2 - D_2^2}{D_1^2}$$

Dimensionless post thickness

$$\frac{t}{D_1}$$

Flow parameters

$$\mathrm{Re}_i = \frac{\rho_1 U_1 D_1}{\mu_1} \qquad \mathrm{Re}_o = \frac{\rho_2 U_2 (D_3 - D_2)}{\mu_2}$$

$$J = \frac{\rho_2 U_2^2}{\rho_1 U_1^2} \qquad r = \frac{U_2}{U_1}$$

$$MR = \frac{\dot{m}_i}{\dot{m}_o}$$

$$s_1 = \frac{\rho_2}{\rho_1} \qquad s_2 = \frac{\rho_3}{\rho_2}$$

Acoustic frequencies

1. Transverse Acoustic mode from chamber/siren
   – f=f(c, geometry)
2. Acoustic modes propellant lines
   – f~c/2L

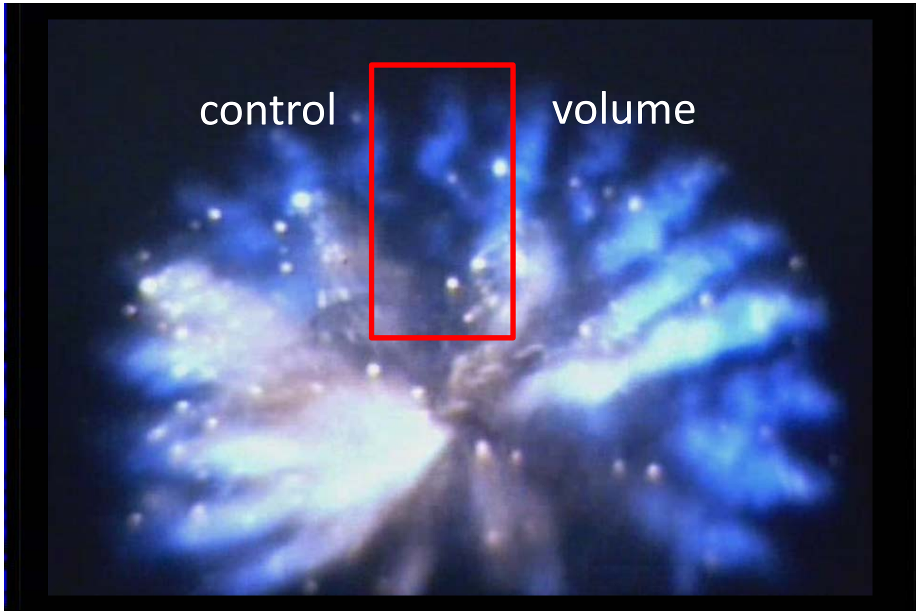
Hydrodynamic frequencies

1. Post wake
   – $St = ft/U_{ch}$
2. Shear layer instabilities
   – $St_q = f\theta/U_{ch}$
3. Jet preferred modes
   – $St = fD_{ij}/U_{ij}$

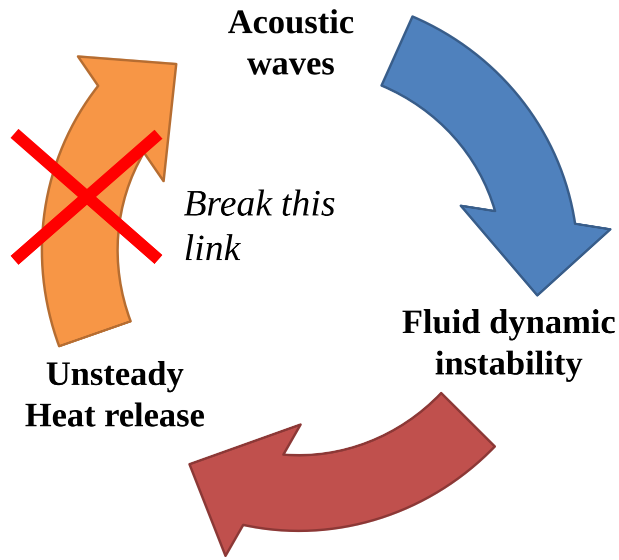
Inflow boundary conditions

- Mean velocity profiles
- RMS fluctuation profiles
- Spectral content

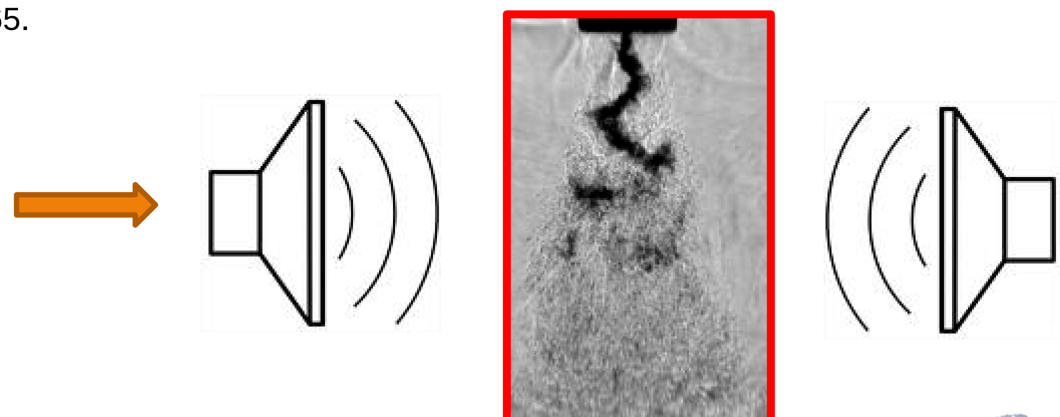
Feedback loop



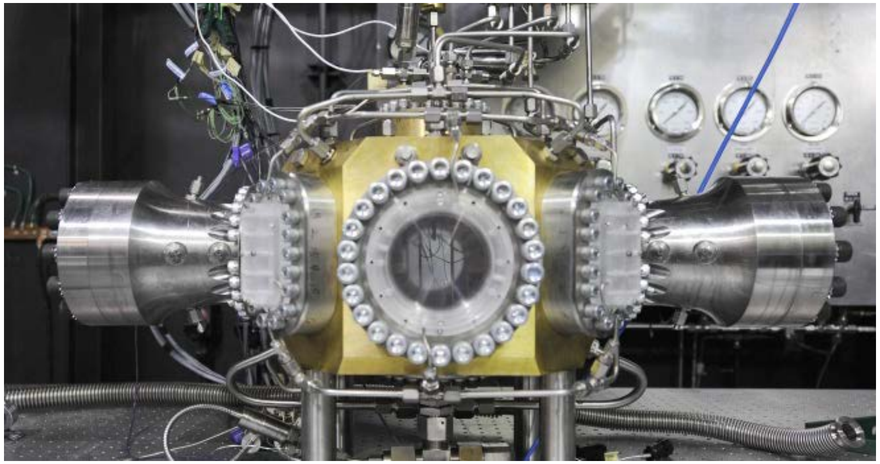
Heidmann, NASA TN D-2725, 1965.



frequency and amplitude controlled independently



New Experimental Facility



Features

– Frequency and amplitude independent of combustion – accurate control of frequency and amp.

– Pressurization independent of combustion – accurate control of pressure.

- Subcritical and supercritical pressures

– Precise cryocooler – accurate control of temperature to within ±1 K.

– Chamber-within-a-chamber

- Outer chamber contains pressure – pressure containing elements remain cool
- Inner chamber contains acoustics and combustion only – allows finer adjustment of inner elements

– High amplitude piezosirens specially designed for high pressure

– On-axis windows for shadowgraph, Schlieren, chemiluminescence, OH* emission

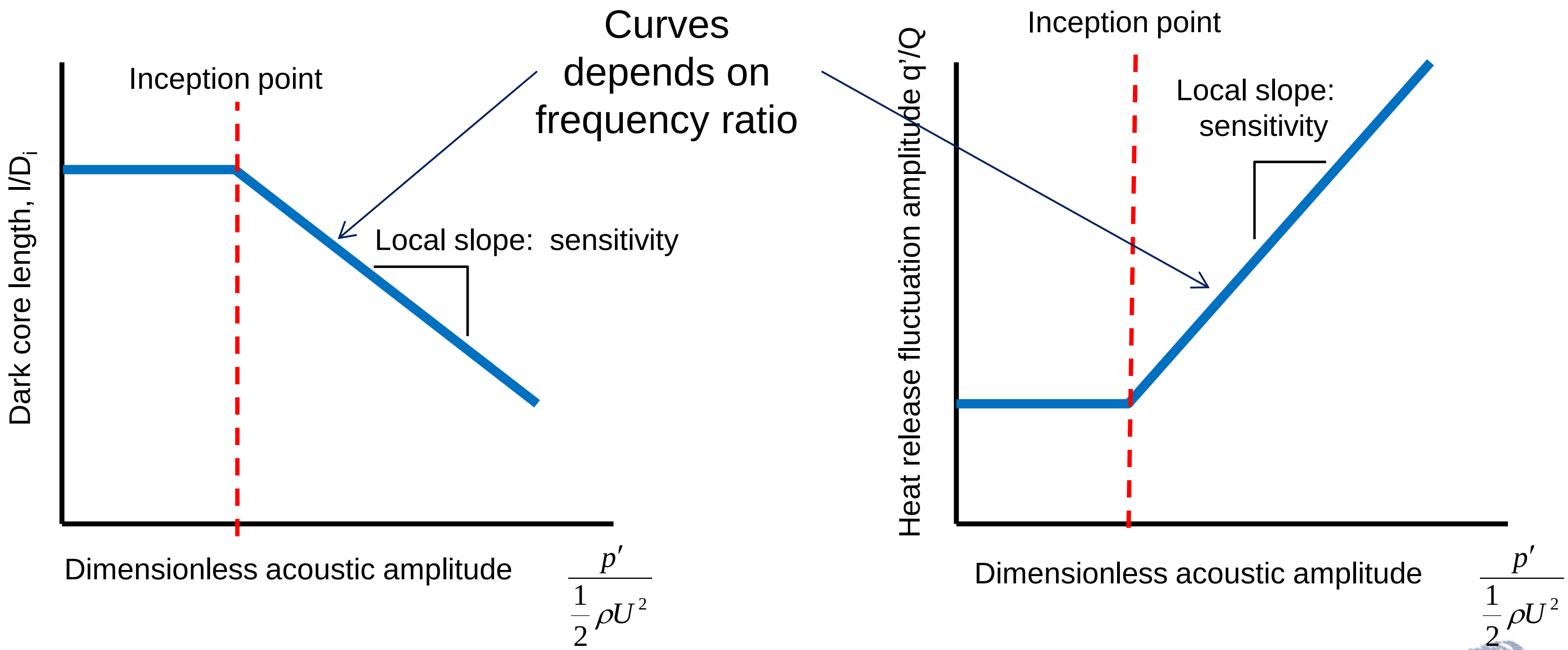
– Off-axis windows for PIV/PLIF

– Fully developed turbulent injector flows – well known boundary conditions

Receptivity

- Shift pressure normalization from chamber pressure to injector dynamic pressure
- Normalize the frequency by the preferred mode of the coaxial jet
- Identify receptivity inception point—threshold for coupling between acoustics and flame

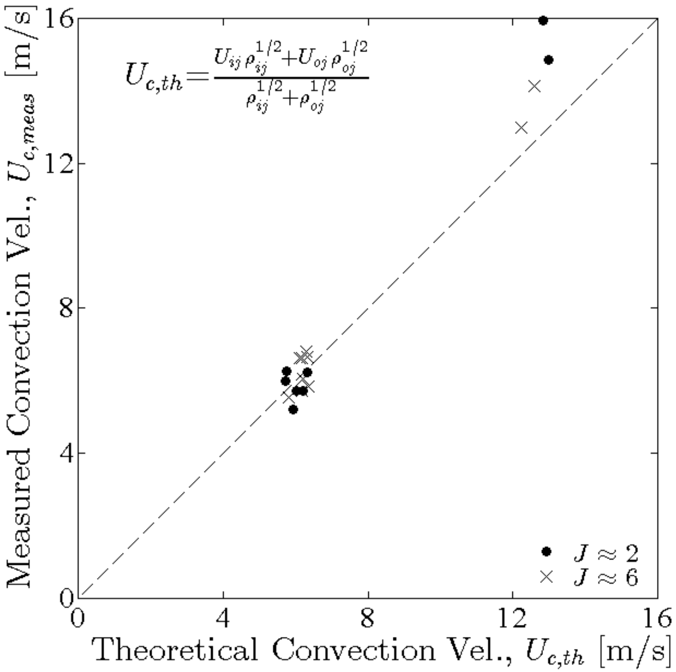
$$P'/\overline{P}_c \rightarrow \frac{P'}{\rho U^2/2} \qquad F = \frac{f_{forcing}}{f_{jet}}$$

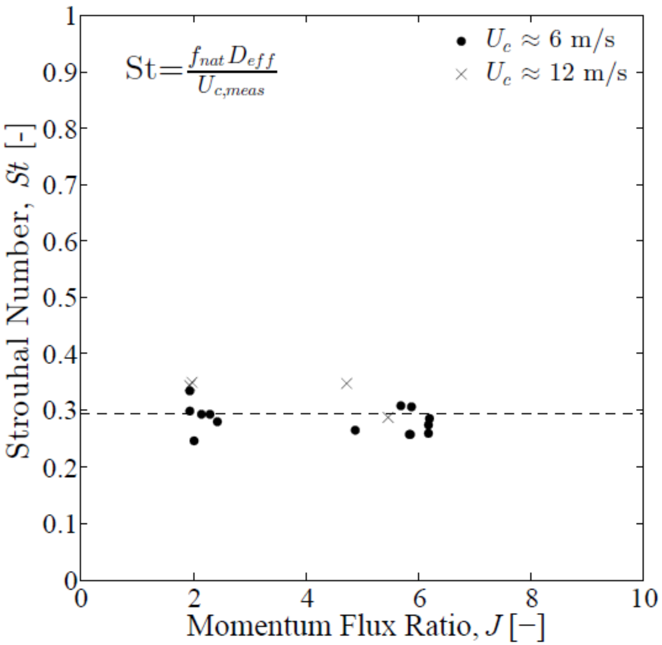


Receptivity Study

Just completed a detailed receptivity study on nonreacting coaxial jets (Wegener Ph.D.)

- **Scaling law for preferred mode frequency for coaxial jet**
- **Verified characteristic velocity for frequency scaling law**
- **Receptivity characteristics for pressure node and anti node conditions for two momentum flux ratios**



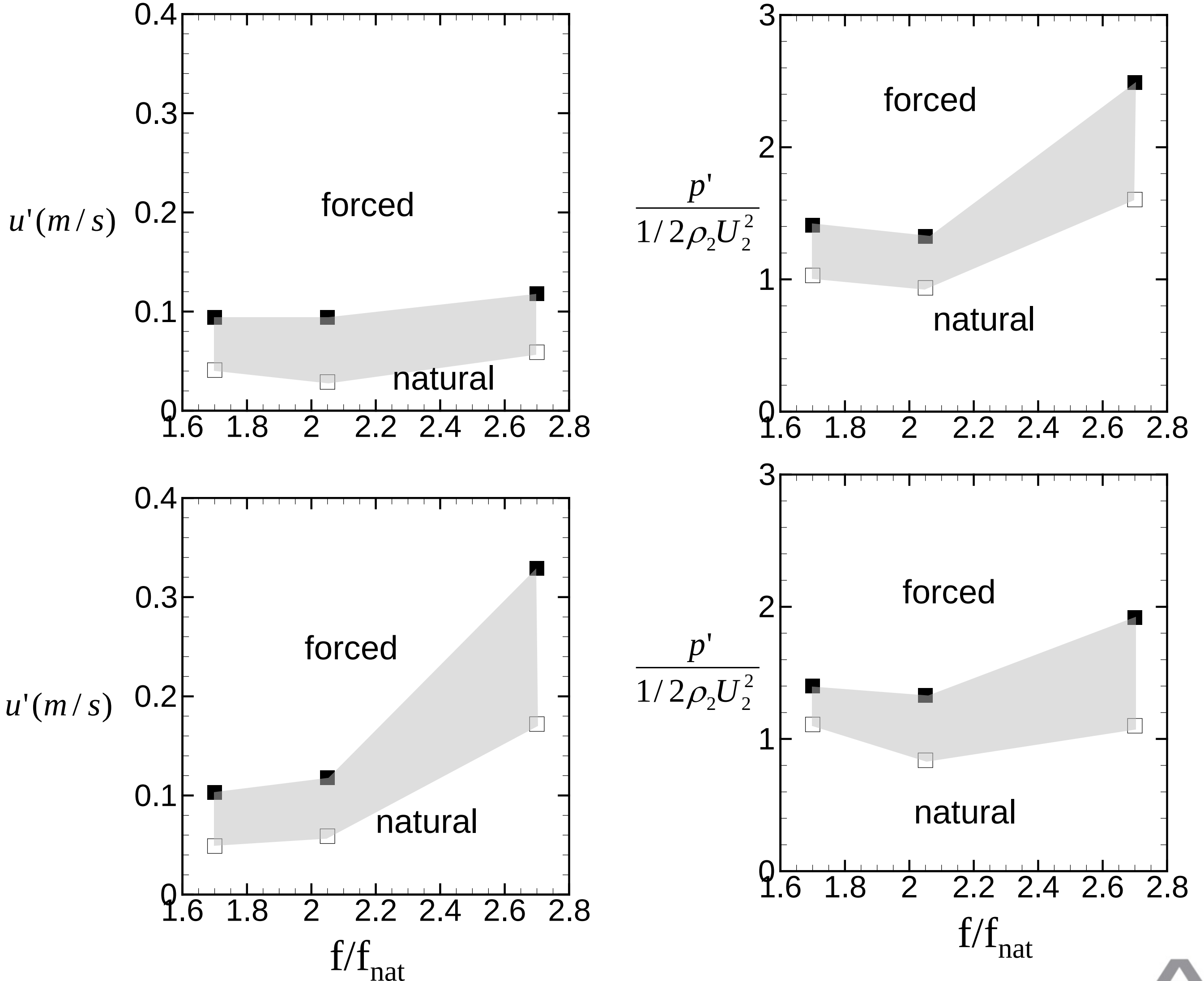


Receptivity

Pressure node | **Pressure antinode**

J = 2

J = 6



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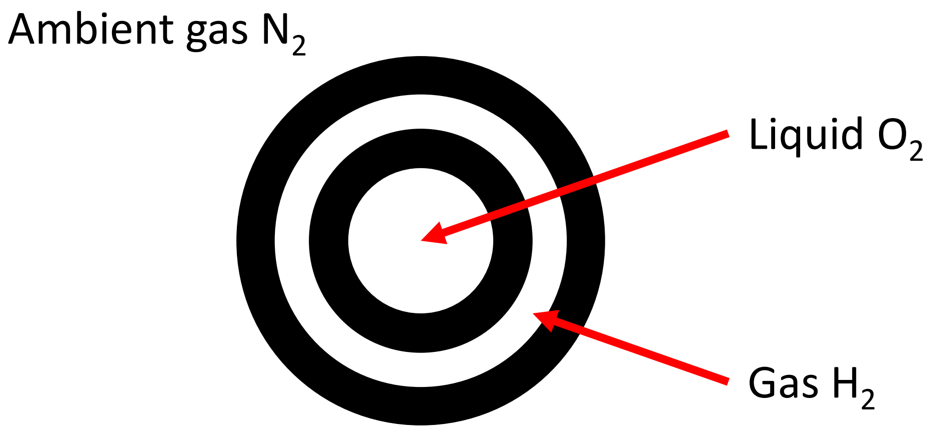
Experimental Conditions

- **New injector**
  - **D_1 = 1.4 mm**
  - **AR = 1.68**
  - **t/D_1 = 0.27**
- **MR = 6**
- **J = 2.7**
- **Liquid O_2 inner jet @ 130 K**
- **Gaseous H_2 @ 250 K**
- **O_2 velocity: 3 m/s**
- **H_2 velocity: 83 m/s**
- **O_2 Re ~ $4.7x10^4$**
- **H_2 Re ~ $2.2x10^4$**
- **Fully-developed turbulent flow conditions**
- **Chamber pressure 3.4 MPa (500 psi)→ subcritical**



Results

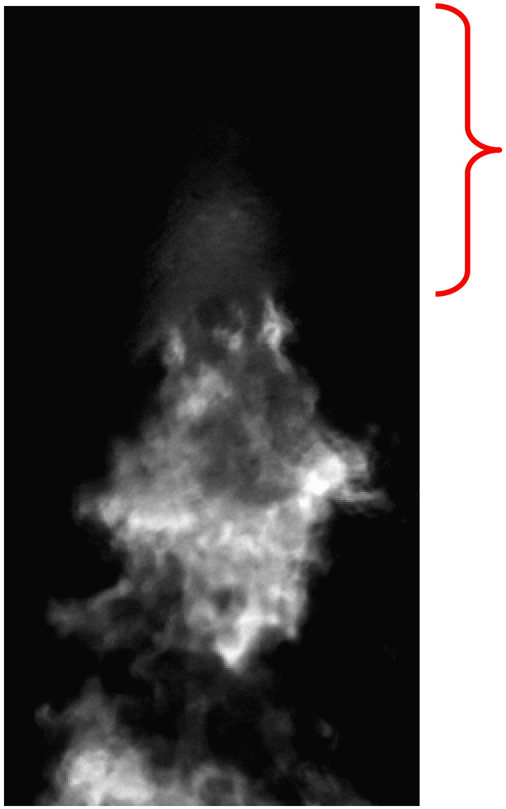
- **Unforced cases**
  - With and without the flame
  - Qualitative features
  - Spectral characteristics
- **Forced cases**
  - With and without the flame
  - Dynamic mode decomposition (DMD) isolation of the forced mode characteristics
  - Pressure node and antinode cases
  - Different frequencies

Unforced Jet/Flame Behavior

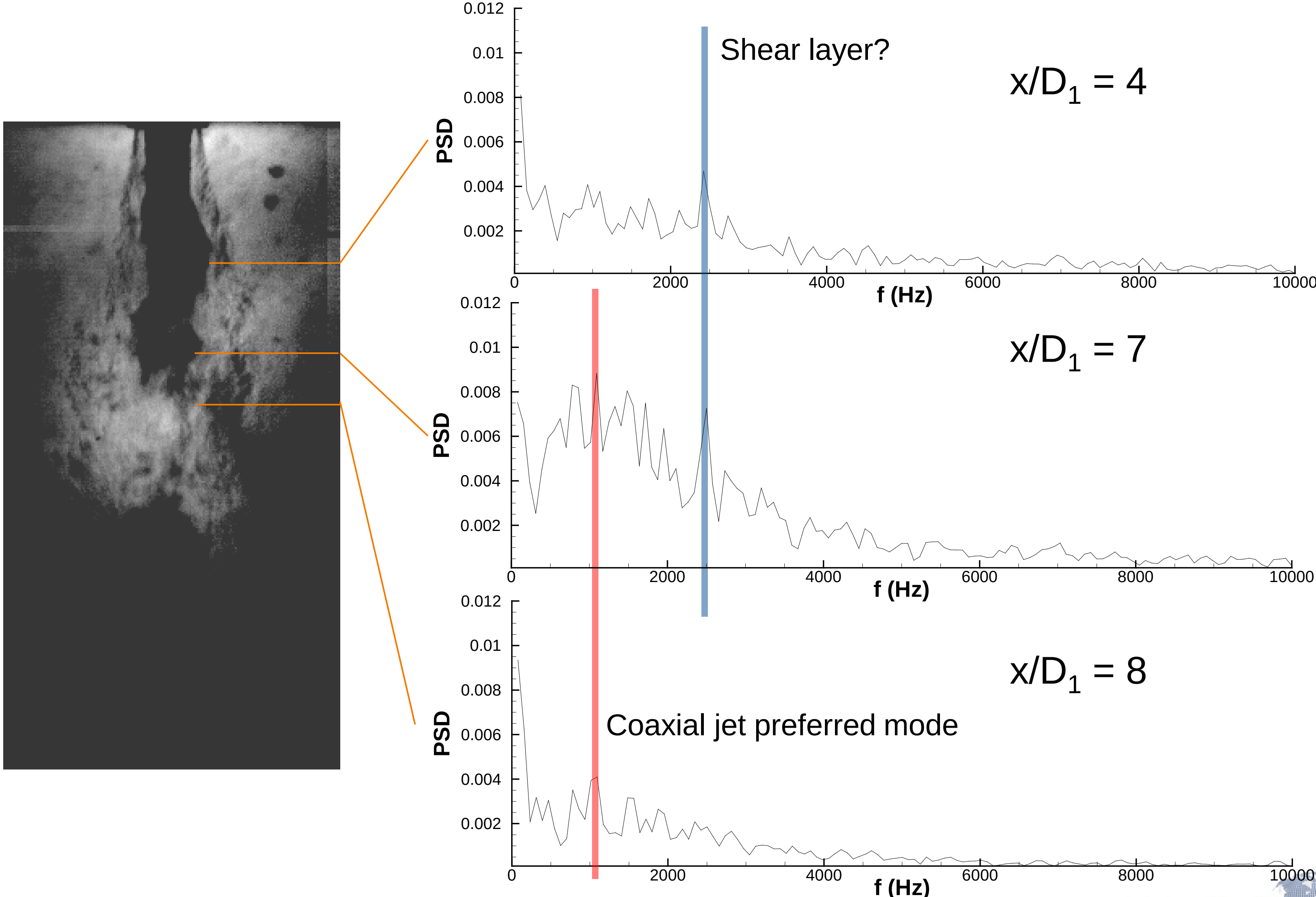
Unfiltered backlit/chemiluminescence

H_2/O_2 no flame

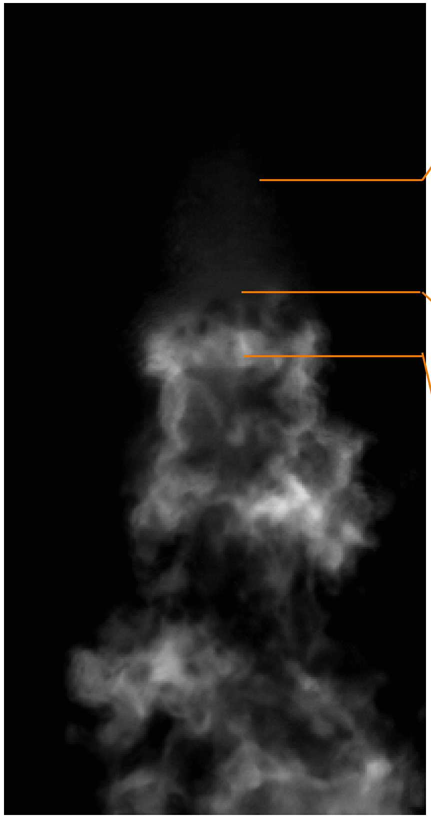
H_2/O_2 with flame

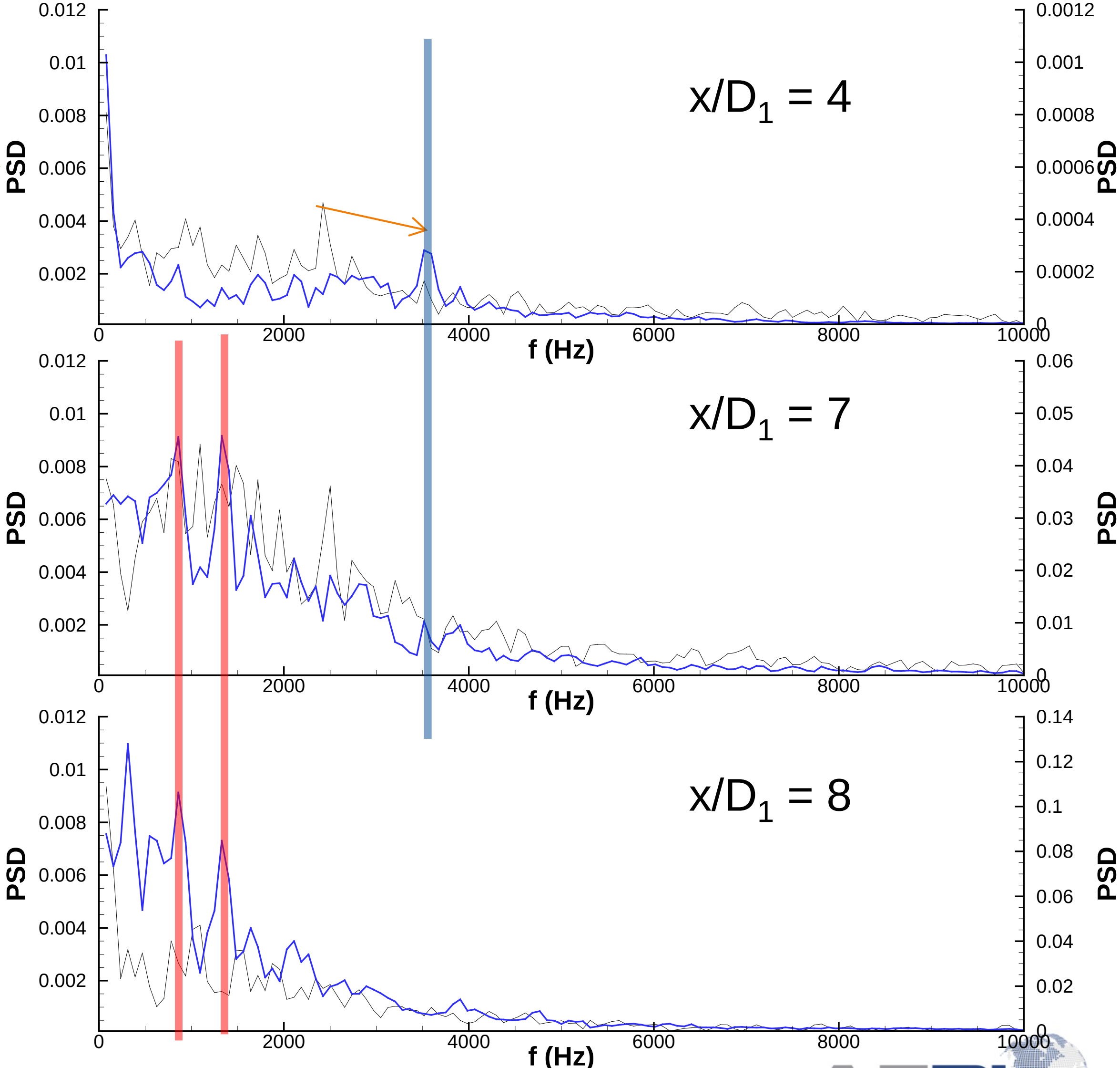


Spectral Features of Unforced Cases

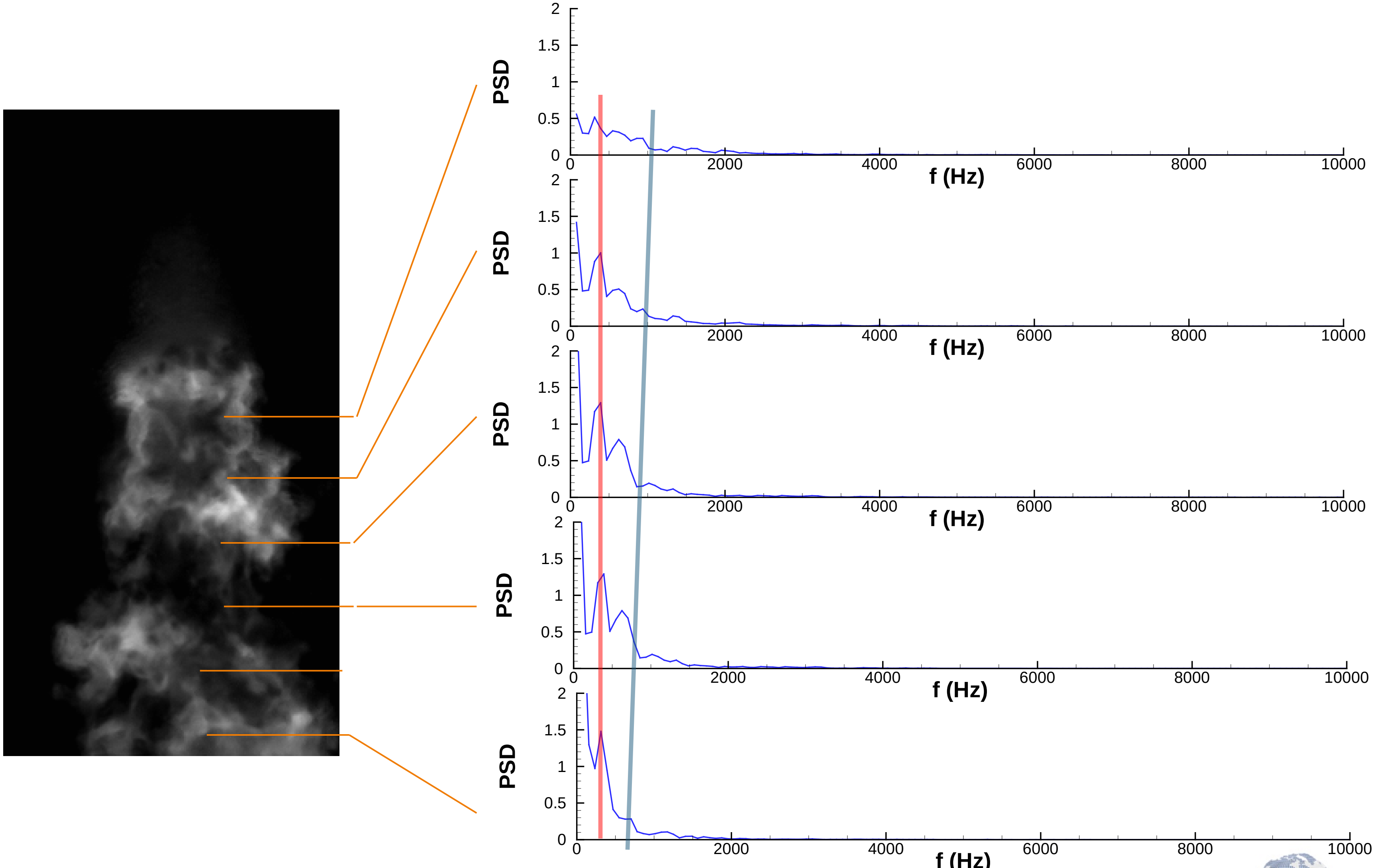


Spectral Features of Unforced Cases





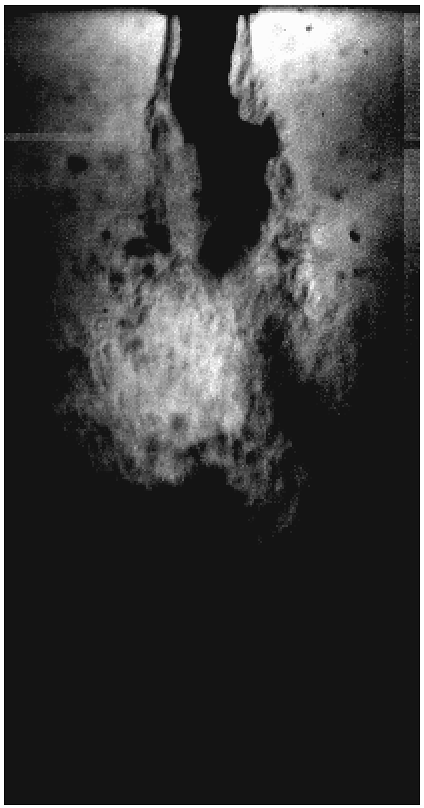
Spectral Features of Unforced Cases



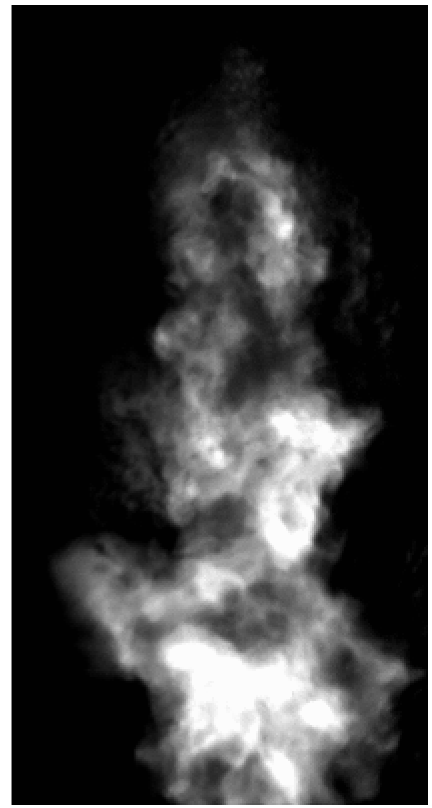
Forced Jets/Flames

Pressure node forcing
1950 Hz, 1.5 V input

H_2/O_2 no flame



H_2/O_2 with flame



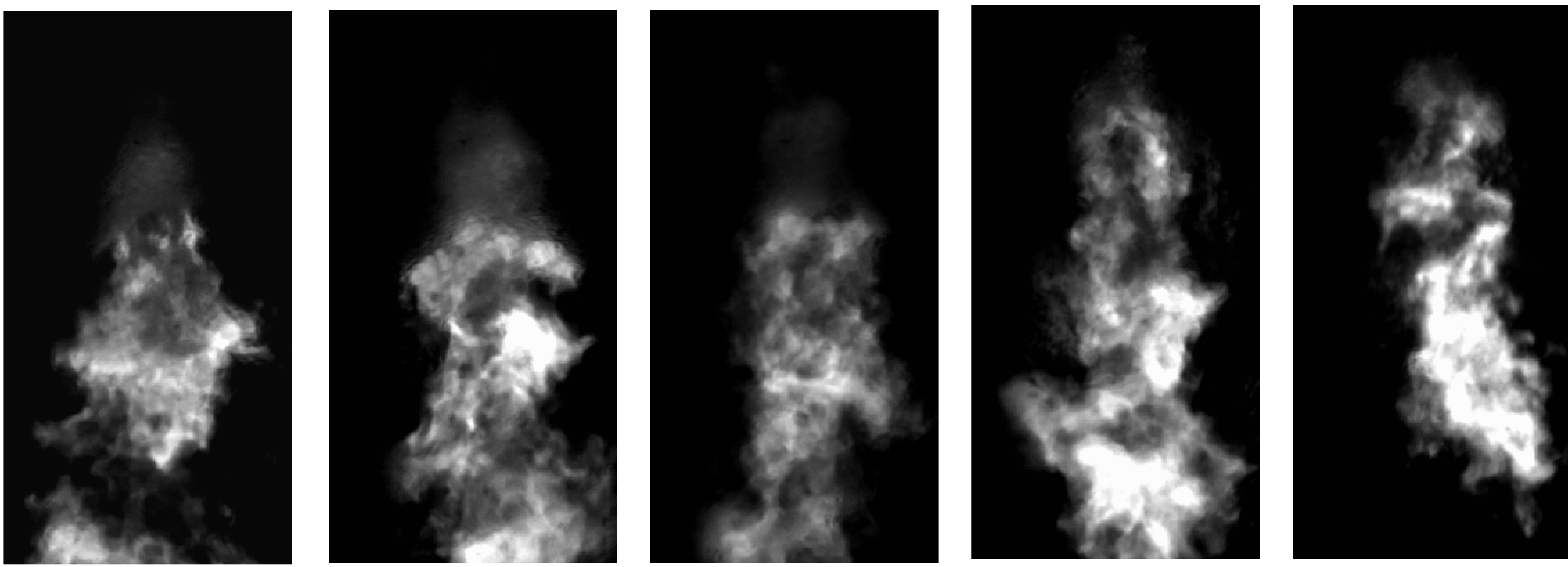
Flame dramatically attenuates the flapping of the jet column, and the LOX core is apparently much longer

Forced Flames

Pressure node forcing

Voltage input to amplitude

0 V | 0.5 V | 1.0 V | 1.5 V | 2.0 V



Increasing forcing strength

DMD Reconstructions

Decomposition/reconstruction Form:

reconstruction

Complex constant

Complex spatial DMD modes

$$I(x,y,t) = \bar{I}(x,y) + \mathrm{Re}\left(\sum_{i=1}^{n} \tilde{A}_i \exp(\tilde{\lambda}_i t)\tilde{D}_i(x,y)\right)$$

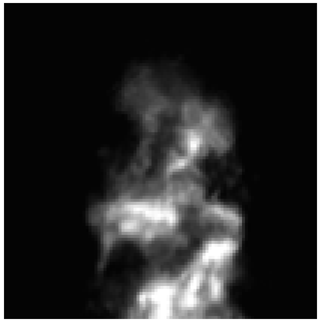
Mean image

Real part only

Complex time dependence

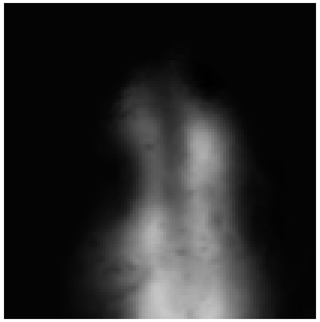
$0 < x/D_1 < 10$

Original data

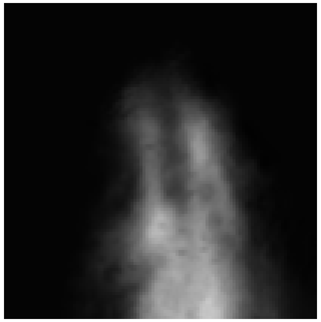


Reconstructions with:

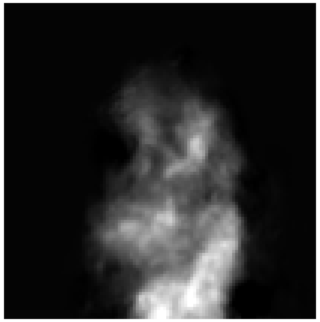
2 modes



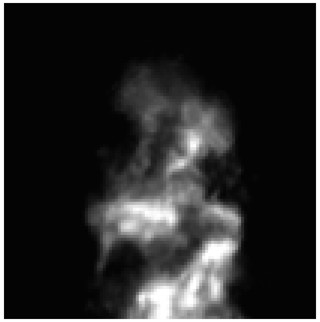
10 modes



100 modes



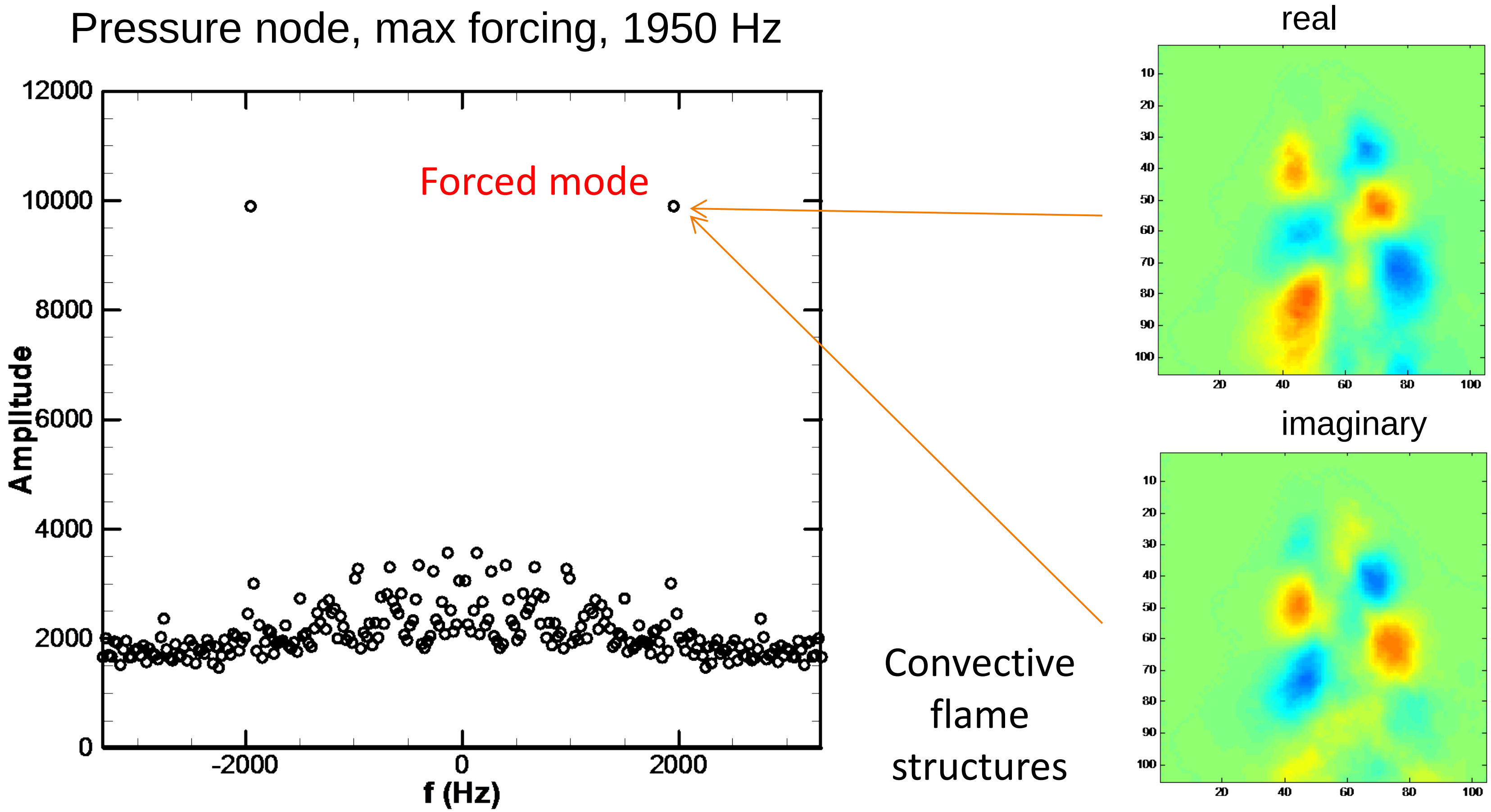
248 (all) modes



Dynamic Mode Decomposition

Dynamic mode decomposition (DMD) applied to first 10 inner jet diameters

Pressure node, max forcing, 1950 Hz

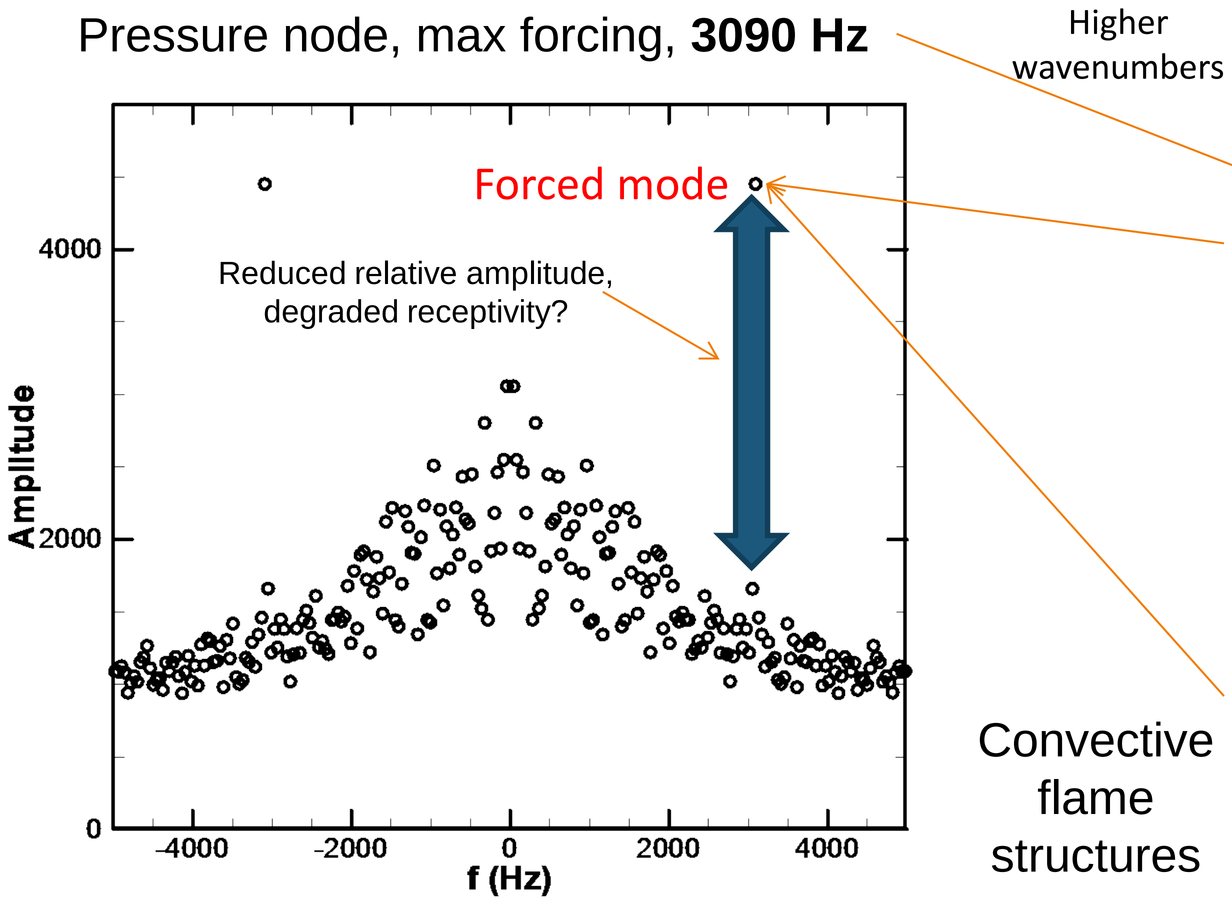


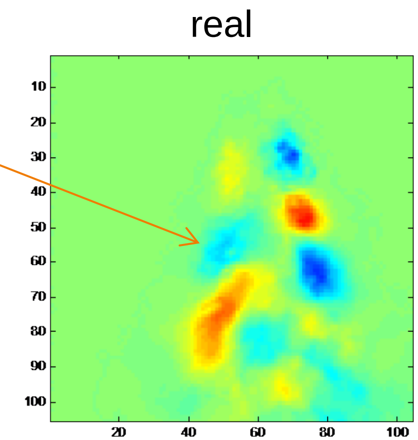
Convective flame structures

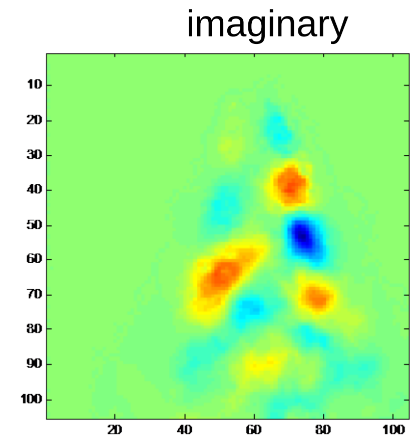
Dynamic Mode Decomposition

Dynamic mode decomposition (DMD) applied to first 10 inner jet diameters

Pressure node, max forcing, **3090 Hz**





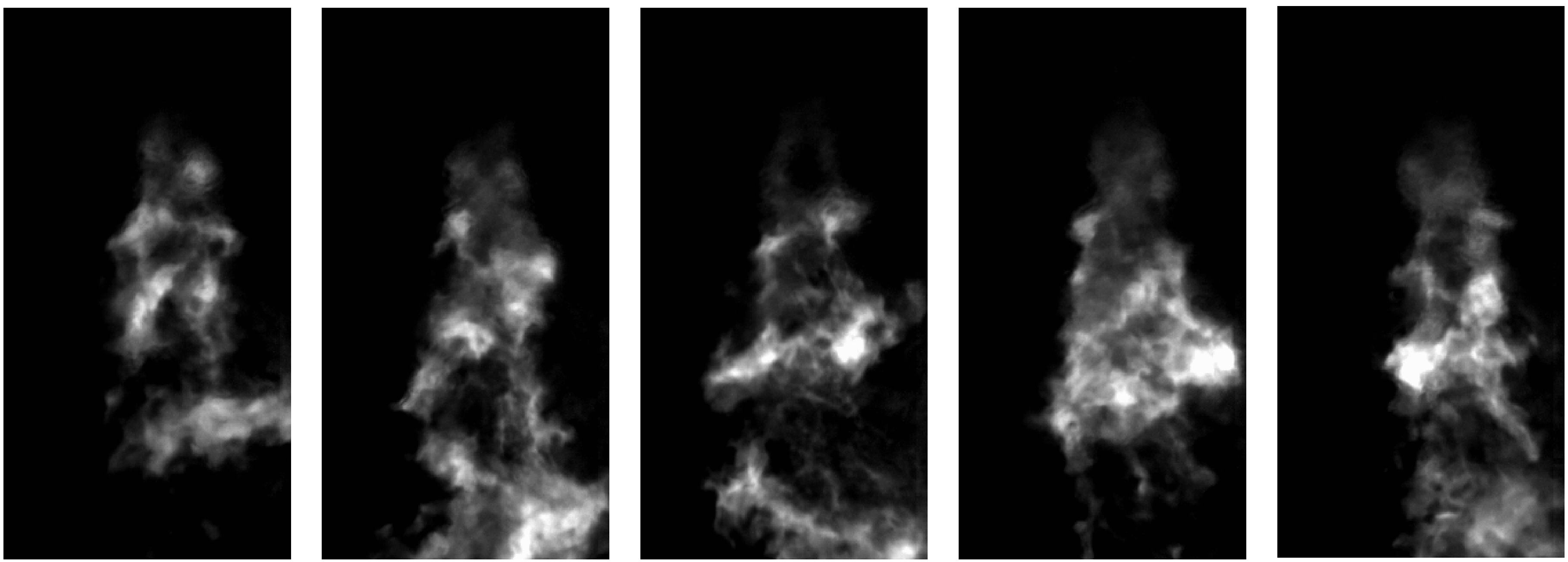


Forced Flames

Pressure antinode forcing

Voltage input to amplitude

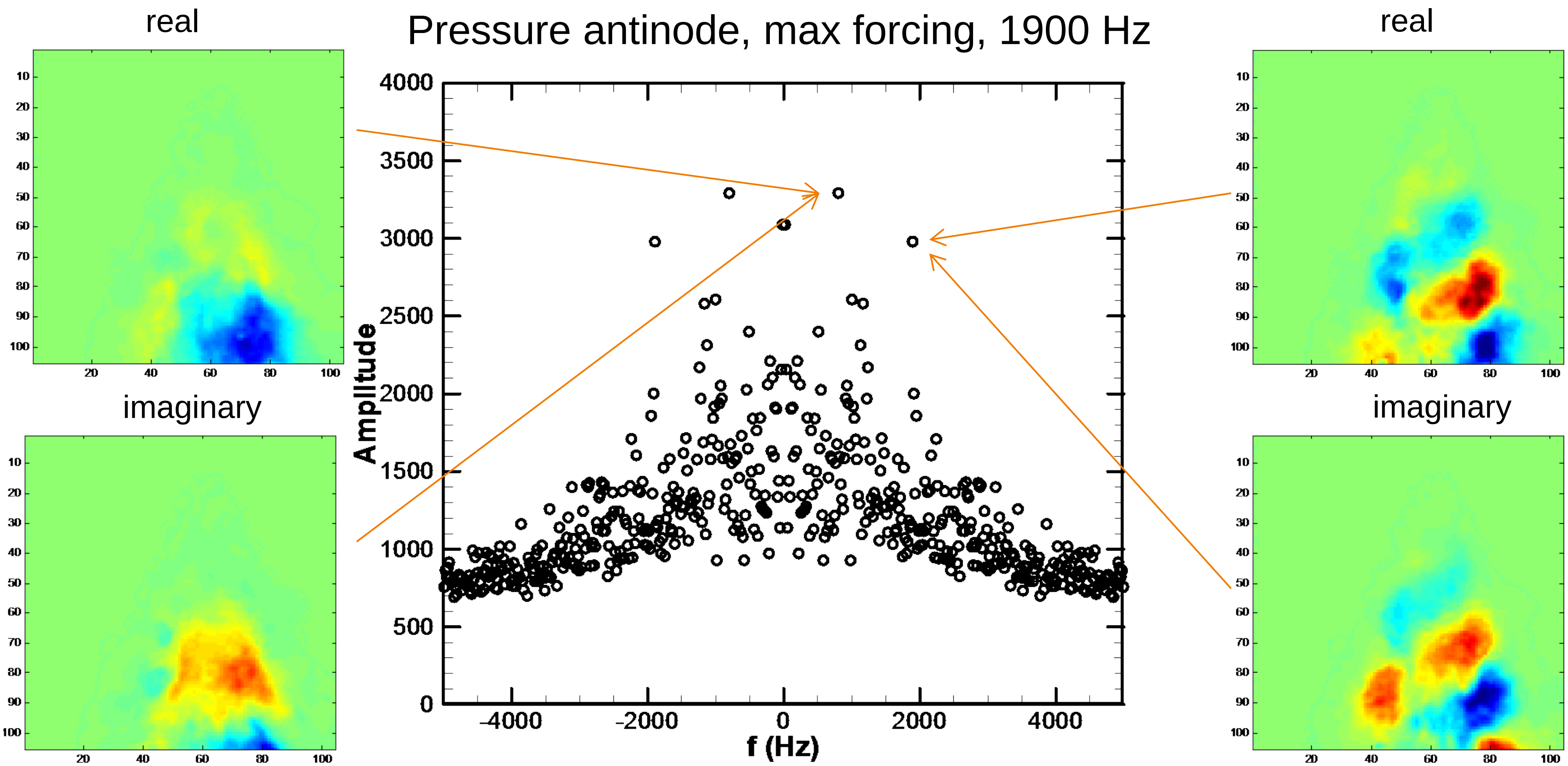
0 V | 0.5 V | 1.0 V | 1.5 V | 2.0 V



Increasing forcing strength

Dynamic Mode Decomposition

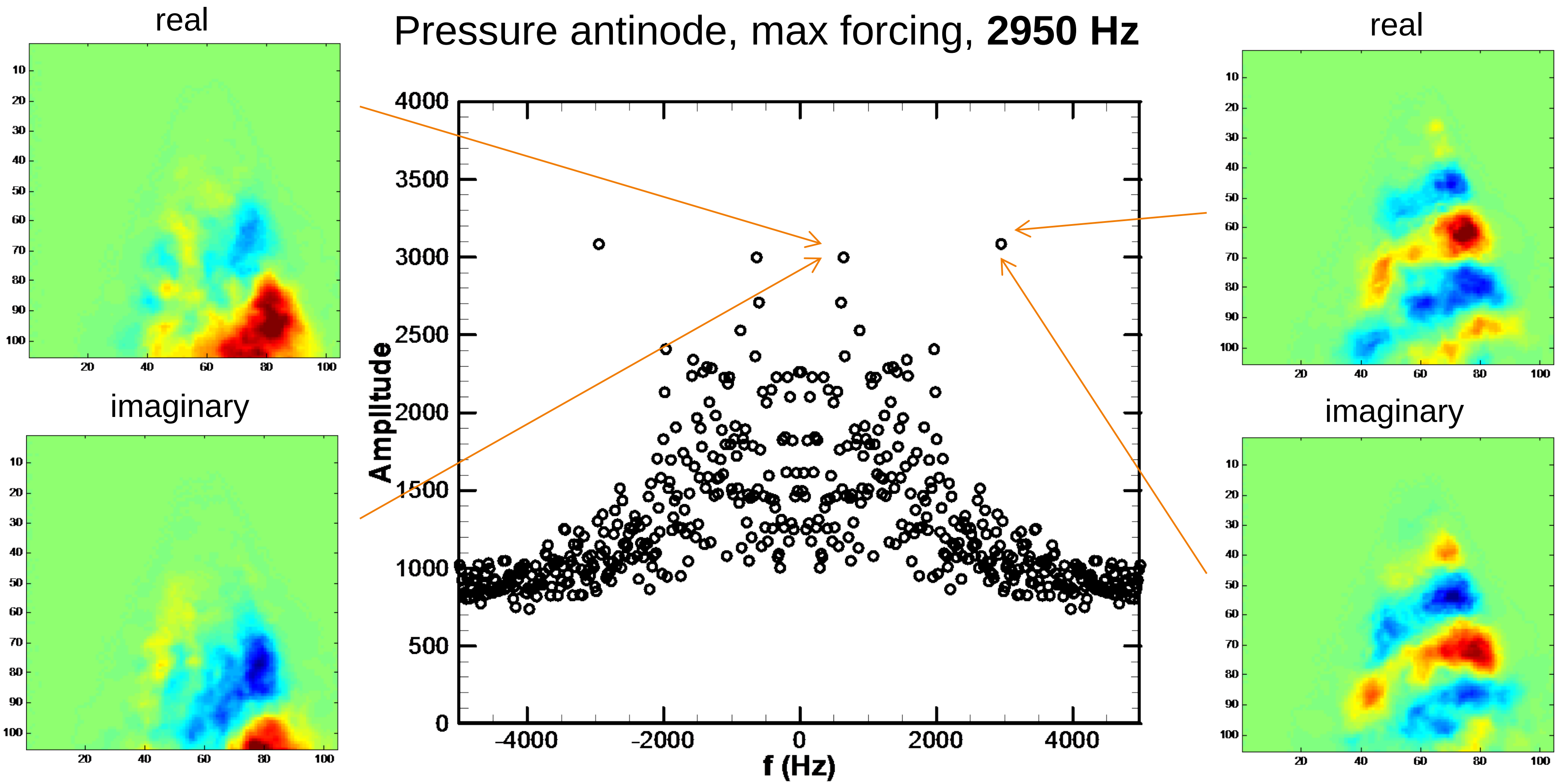
Dynamic mode decomposition (DMD) applied to first 10 inner jet diameters



AFRL

Dynamic Mode Decomposition

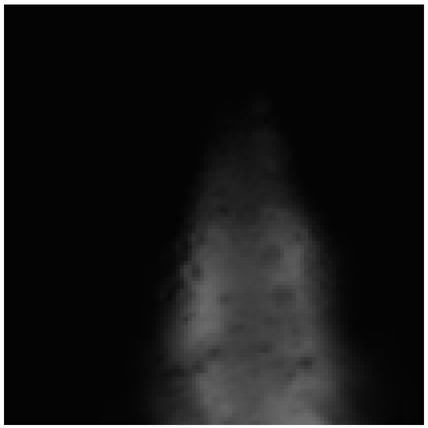
Dynamic mode decomposition (DMD) applied to first 10 inner jet diameters



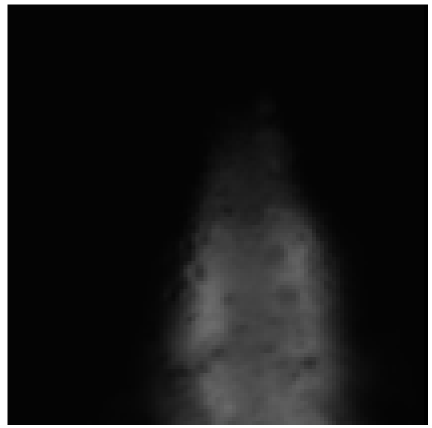
DMD Reconstructions

Pressure antinode, max forcing, **2950 Hz**

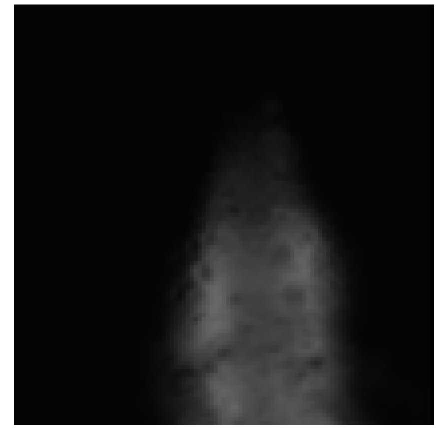
2 modes



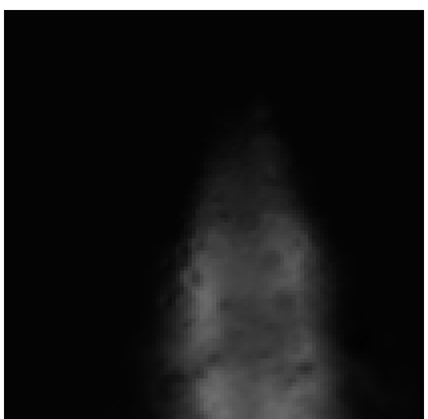
4 modes



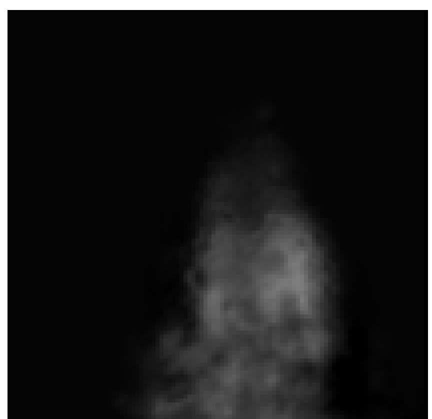
6 modes



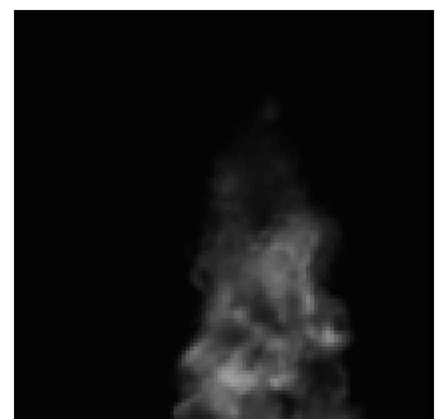
10 modes



100 modes

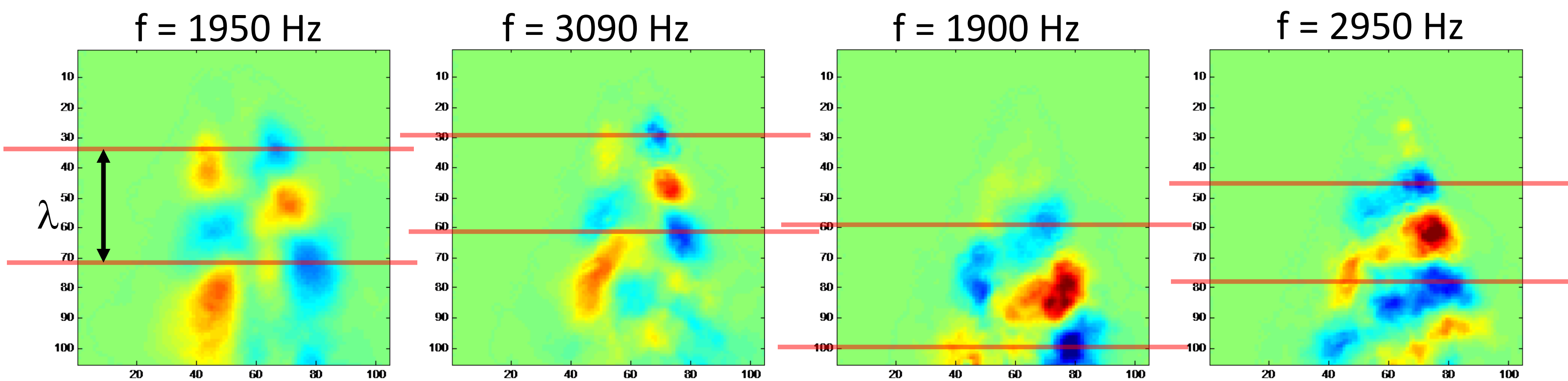


548 modes



Convection Velocities

$$U_c = f\lambda$$



$\lambda = 2.7\ \mathrm{mm}$	$\lambda = 2.2\ \mathrm{mm}$	$\lambda = 2.8\ \mathrm{mm}$	$\lambda = 2.3\ \mathrm{mm}$
$U_c = 5.3\ \mathrm{m/s}$	$U_c = 6.8\ \mathrm{m/s}$	$U_c = 5.3\ \mathrm{m/s}$	$U_c = 6.8\ \mathrm{m/s}$

Burning structures travel slower than the estimated convection velocity based on the Dimotakis (1986) expression of 7.5 m/s.

$$U_c = \frac{\rho_1^{1/2} U_1 + \rho_2^{1/2} U_2}{\rho_1^{1/2} + \rho_2^{1/2}}$$

Conclusions

- **Unforced reacting and nonreacting H_2/O_2 flows**
  - Flame appears to delay mixing and lengthen the liquid core length
  - Slight changes in spectral content
- **Forced flames**
  - Qualitatively similar to nonreacting forced coaxial flows
  - Pressure node forcing
    - Flame response is antisymmetric
    - Potentially degraded response at higher frequency
  - Pressure antinode forcing
    - No obvious changes in the raw images
    - DMD extracts the spatial mode responding to the forcing
    - Response seems to be tilted axisymmetric mode or possibly a combination of axisymmetric and helical modes

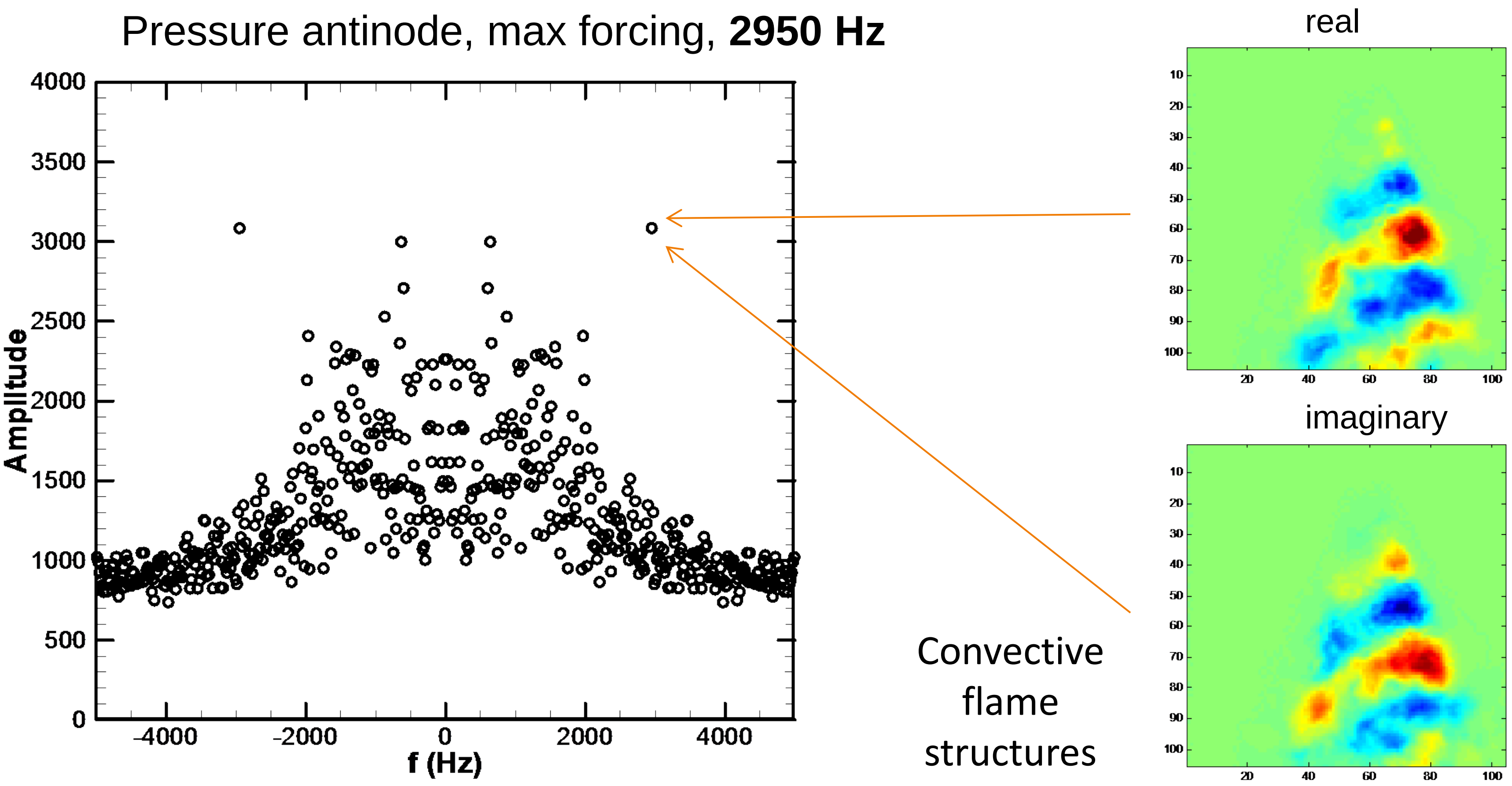
What's Next?

- **More detailed quantification of the spectral content in unforced coaxial jet flames**
  - Effects of flame sheet on frequency content
  - Isolation and scaling of dominant "preferred modes"
  - Search for injector conditions with strong inner-post wake instabilities
- **Forced flames**
  - Detailed exploration of relative frequency and amplitude
  - OH* chemiluminescence
  - Different injector flow conditions
  - Quantitative optical diagnostics (OH PLIF)

Dynamic Mode Decomposition

Dynamic mode decomposition (DMD) applied to first 10 inner jet diameters

Pressure antinode, max forcing, **2950 Hz**



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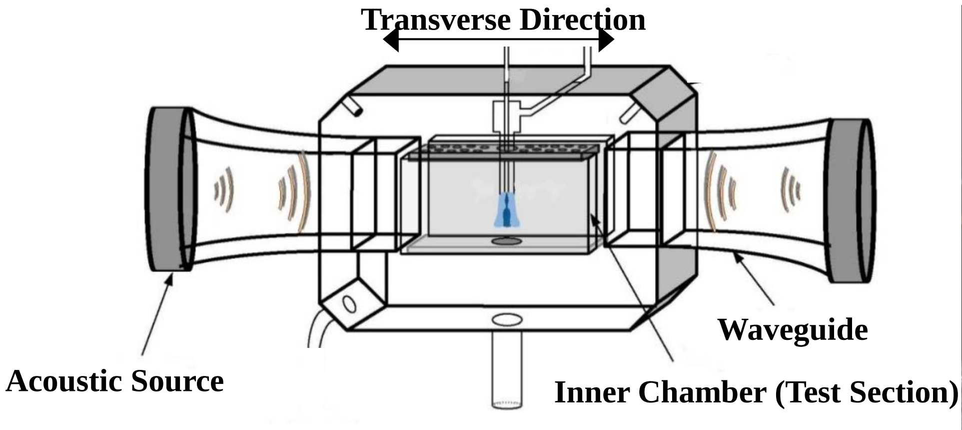
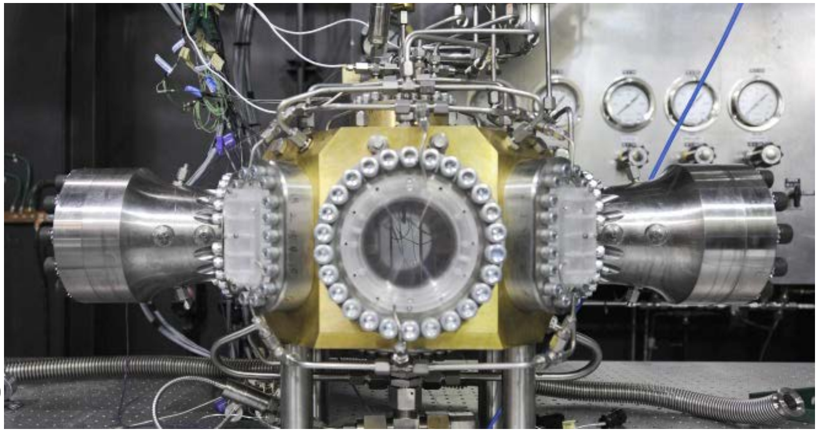
New Experimental Facility





Capabilities

- Cryogenic propellant temperature control with high accuracy (±1 K)
- Sub- and super-critical chamber pressure (p_c up to 10.4 MPa)
- High amplitude acoustic forcing (p'/p_c ~ 0.02)
- Coaxial injector with extended length for fully developed turbulent flow (l_e/D > 110)
- High-speed diagnostic tools
    - Pressure transducer(s) natural frequency > 100 kHz
    - Time-series backlit imaging (f > 25 kHz)
    - Off-axis windows for future PIV/PLIF measurements