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Acoustically Forced Coaxial Hydrogen / Liquid Oxygen Jet Flames

ILASS Americas 28th Annual Conference on Liquid
Atomization and Spray Systems
Dearborn, MI, May 2016



Mario Roa, Dave Forliti, Sierra Lobo, Inc.
Al Badakhshan, ERC Inc.
Doug Talley, AFRL



AF relevant considerations



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



Objectives

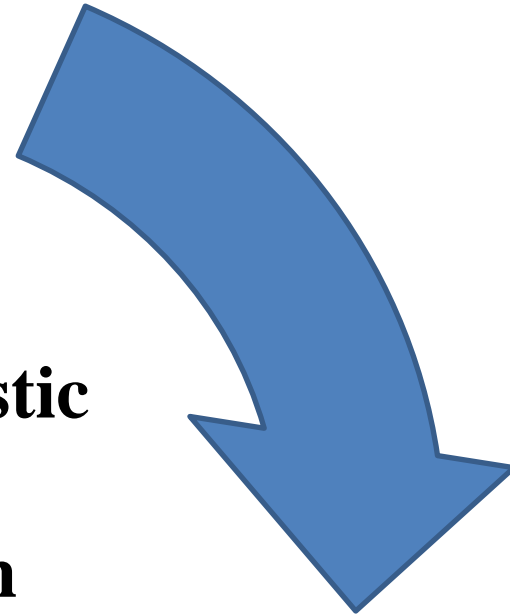


- **Determine the mechanisms governing the dynamics of a high pressure, chemically reacting, multiphase, acoustically driven, shear flow in the form of a coaxial jet flame.**
- **Explore how the presence of chemical reactions affects the response of coaxial jets to acoustic forcing.**
- **Explore inter-element interactions.**



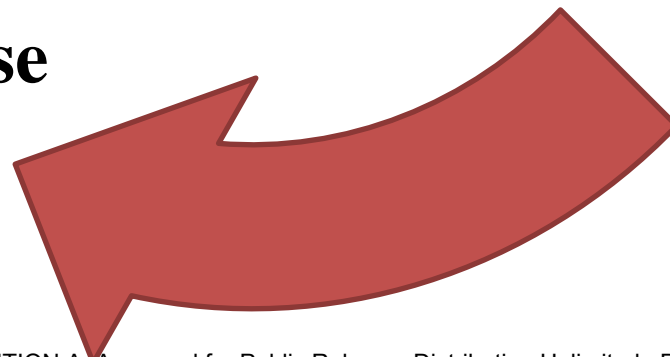
Approach

Acoustic waves

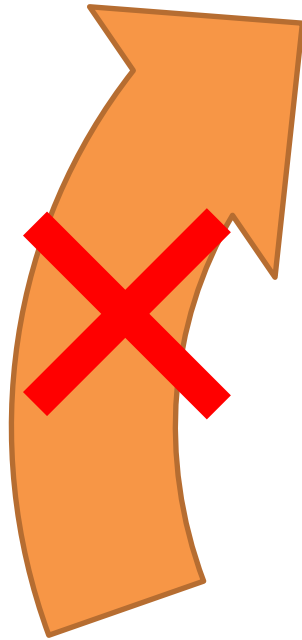


Hydrodynamic response

Thermoacoustic Instability Mechanism



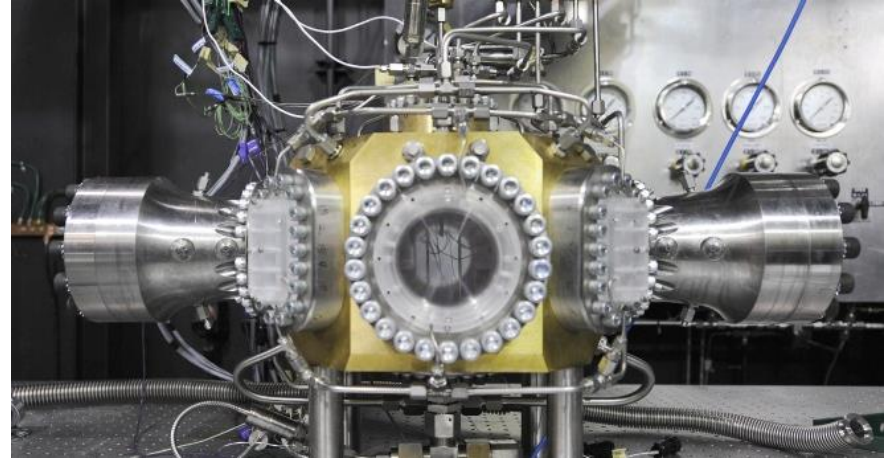
Unsteady Heat release



Open the loop for better control



Experimental Facility



Features

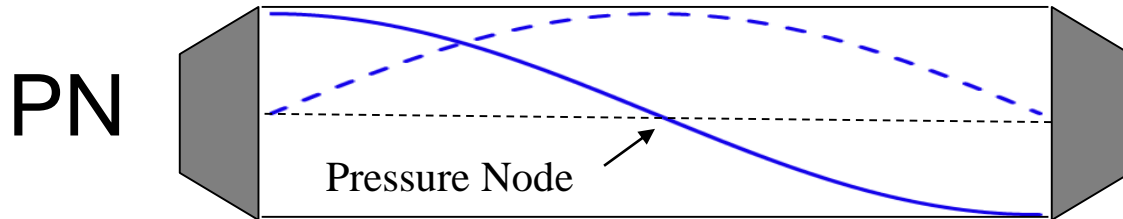
- Frequency and amplitude independent of combustion – accurate control of frequency and amp.
 - Pressurization independent of combustion – accurate control of pressure.
 - Subcritical and supercritical pressures
 - Precise cryocooler – accurate control of temperature to within ± 1 K.
 - Chamber-within-a-chamber
 - 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
 - High-speed pressure transducers
- Rayleigh Index fields



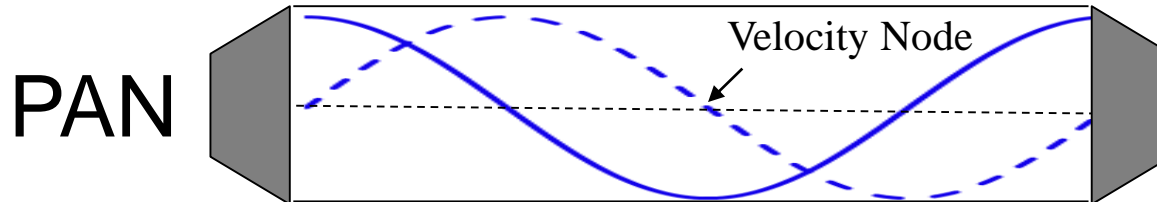
Summary of Forcing Conditions



- **Pressure node (PN) and pressure antinode (PAN) at the injector location**



Imposes transverse velocity oscillation



Imposes unsteady backpressure

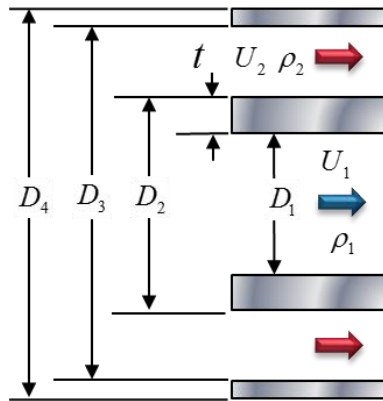
- **Forcing frequency ~ 3000 Hz**
- **Pressure fluctuation amplitudes (peak-to-peak) range up to approximately 9 psi (6 psi reacting)**



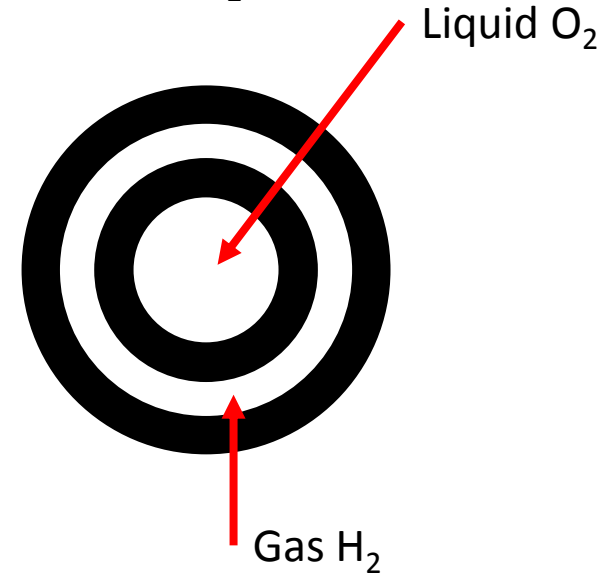
Operating Conditions



- **Cryogenic liquid O₂ and gaseous H₂ flame**
- **Injector geometry**
 - $D_1 = 1.4$ mm
 - $AR = 1.68$
 - $t/D_1 = 0.27$
- **$J \approx 2.2$**
- **$MR \approx 6-7$**
- **O₂ inner jet @ 140 K**
- **H₂ outer jet @ 250 K**
- **Fully-developed turbulent flow conditions**
- **Chamber pressure 3.4 MPa (500 psi) → subcritical**



Ambient gas N₂



Liquid O₂

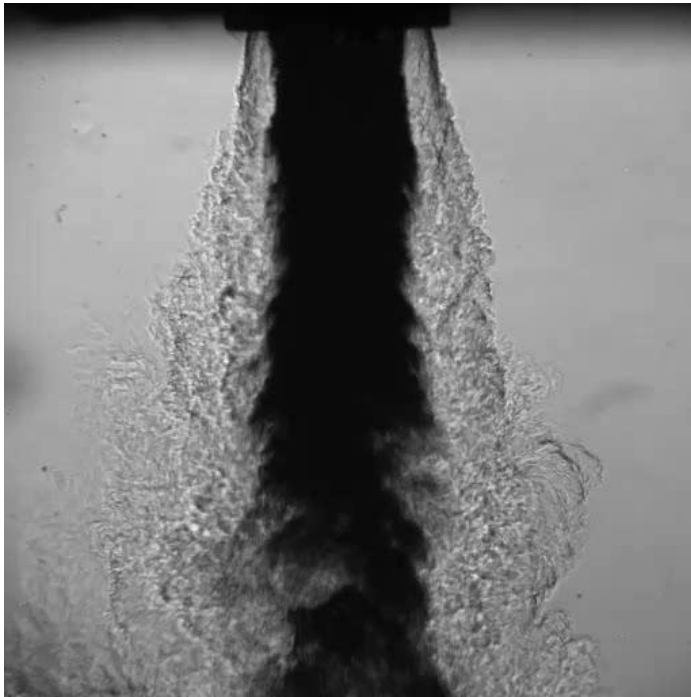
Gas H₂



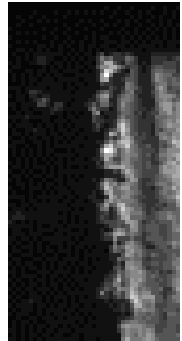
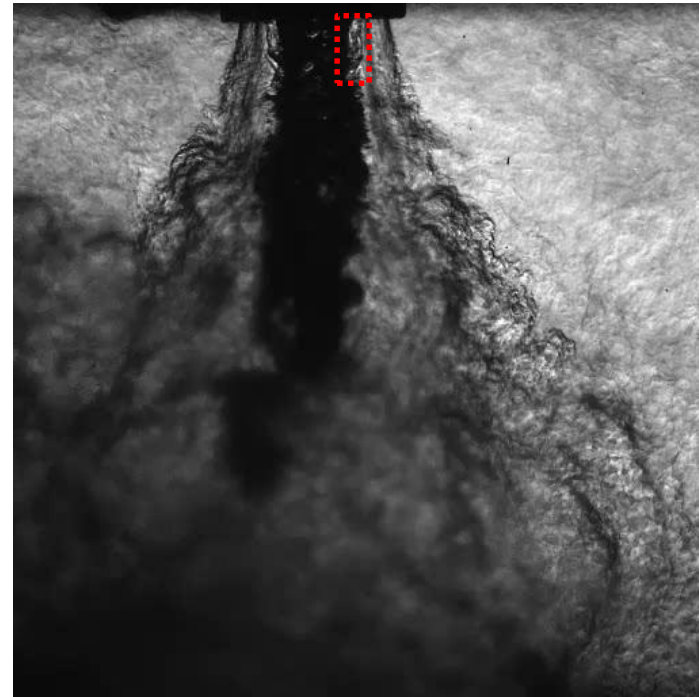
Unforced Results



Nonreacting



Reacting



Differences:

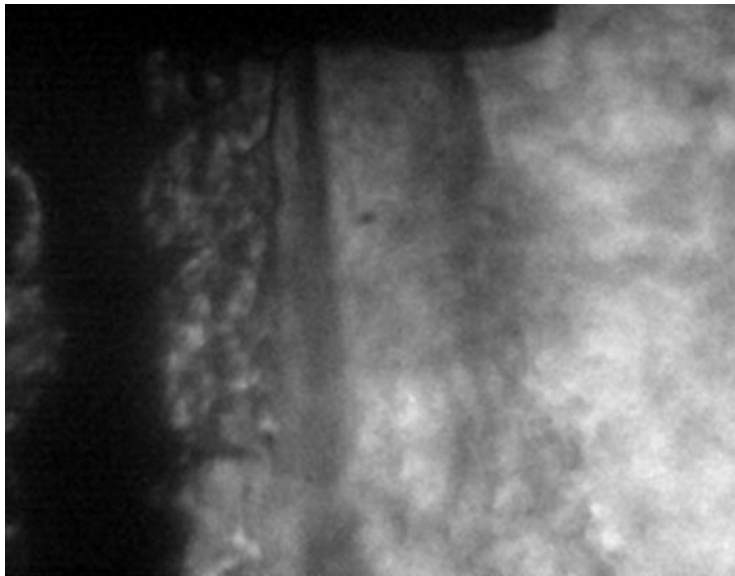
- Flame reduces fine fibrous structure of liquid oxygen surface topology
- Flame increases the characteristic time scales of the liquid structures
- Flame allows optical access to recirculation zone—reverse flow observed



Recirculation Zone Phenomenon



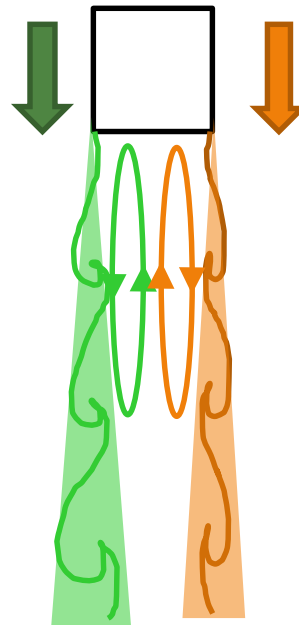
Combustion case



100kHz Framerate

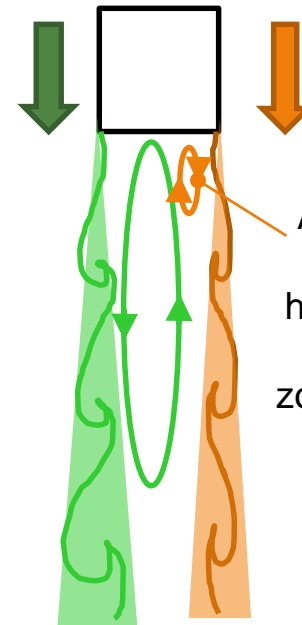
Symmetric recirculation zones

Low-speed liquid O_2 High-speed gaseous H_2



Asymmetric recirculation zones

Low-speed liquid O_2 High-speed gaseous H_2



Although not observed, hydrogen side recirculation zone should be present

Results show large oxygen-side recirculation zone that brings liquid O_2 structures very close to hydrogen shear layer.

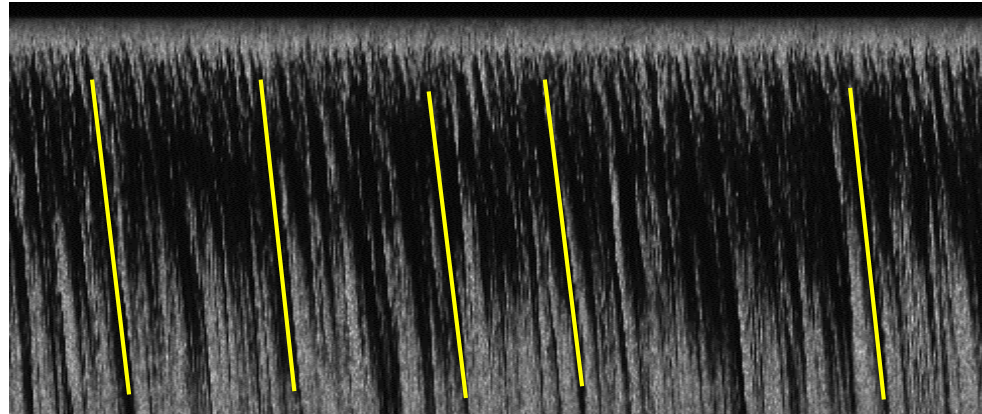
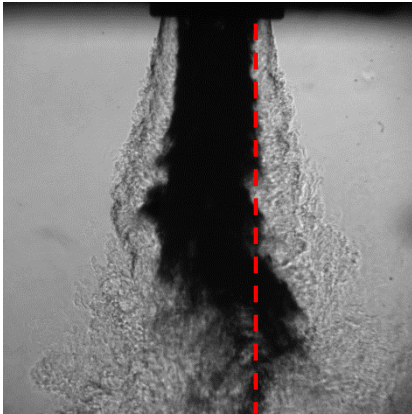


Convection Velocities



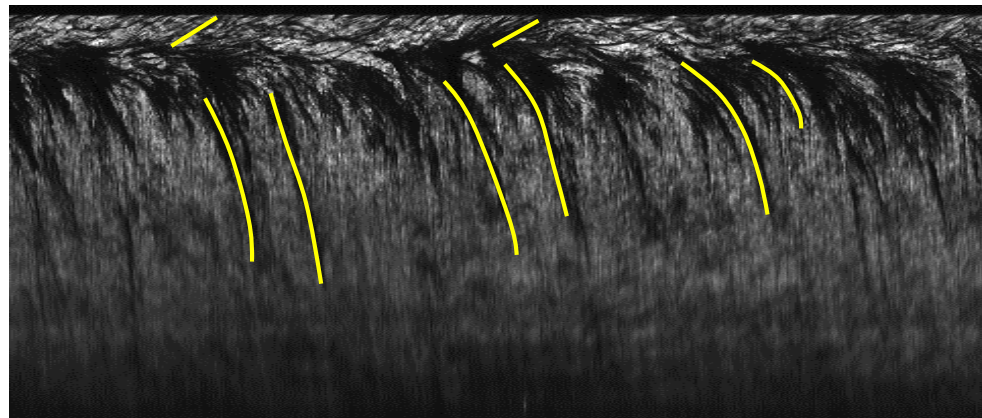
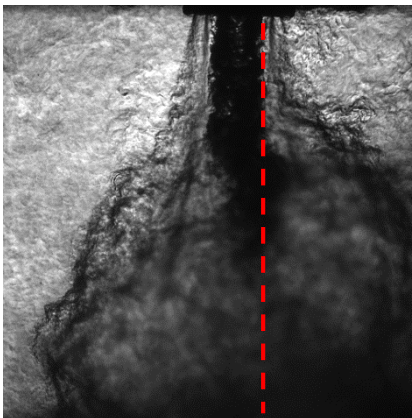
Extract column of pixels at each time along shear layer edge as a function of time, dark streaks represent convecting liquid structures

x
y



Structures convect at apparent constant velocity

time



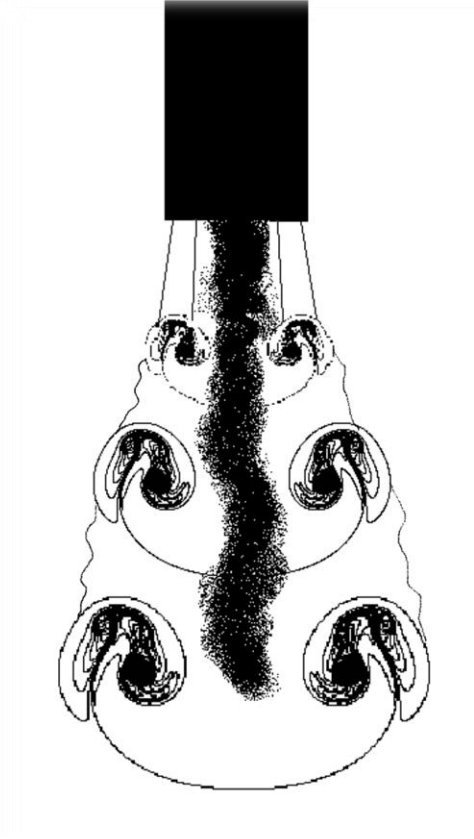
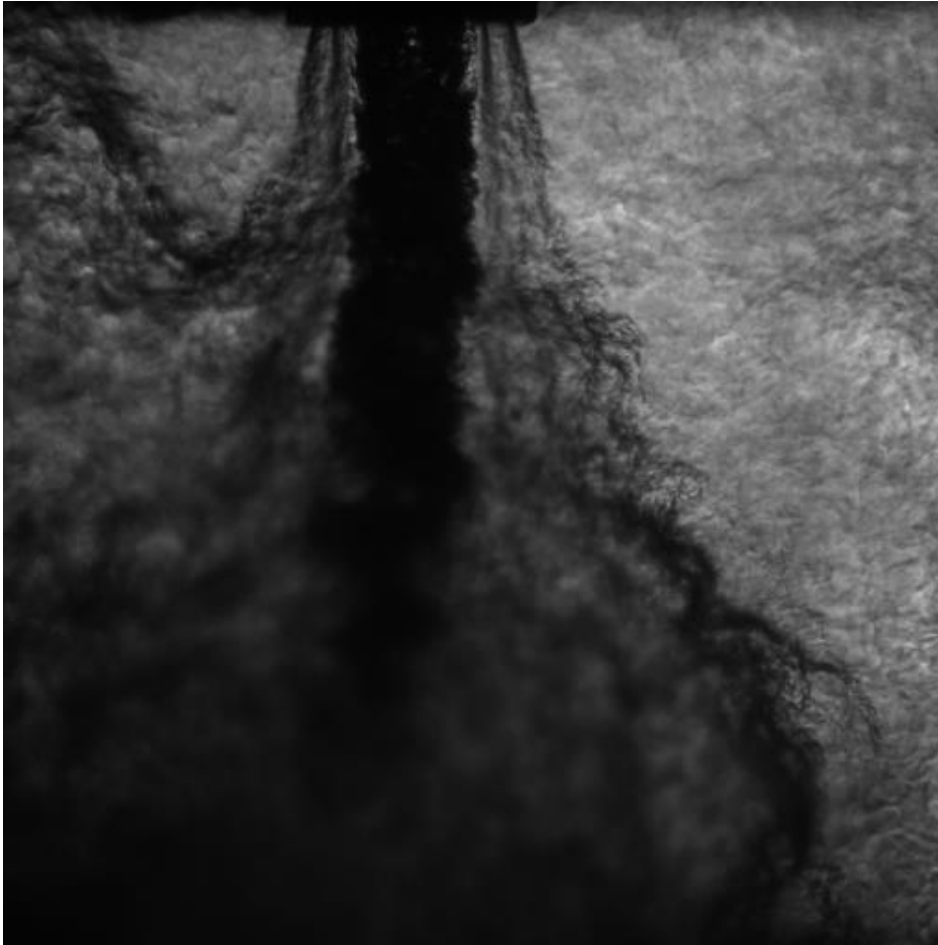
} Positive slope streaks represent upstream traveling features

Structures start at slow speed and gradually accelerate with downstream distance

time



Downstream combustion structures

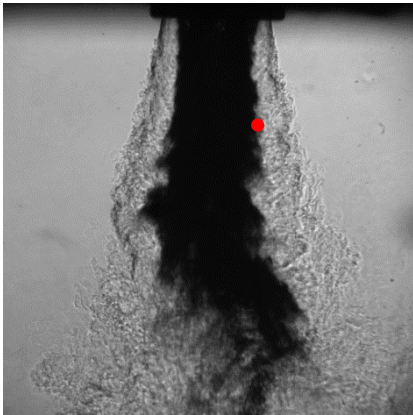




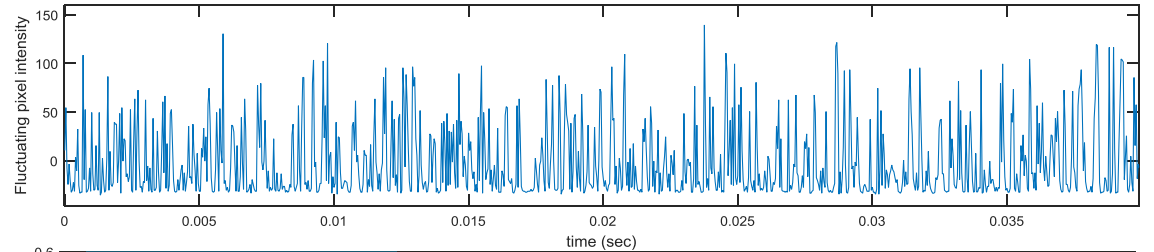
Near Field Shear Layer Dynamics



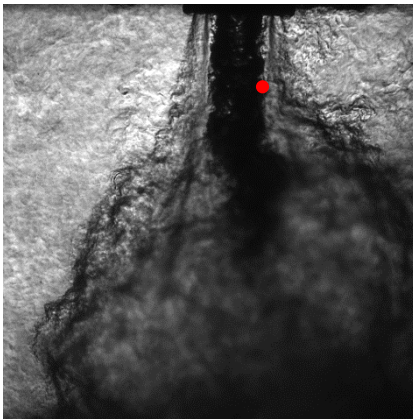
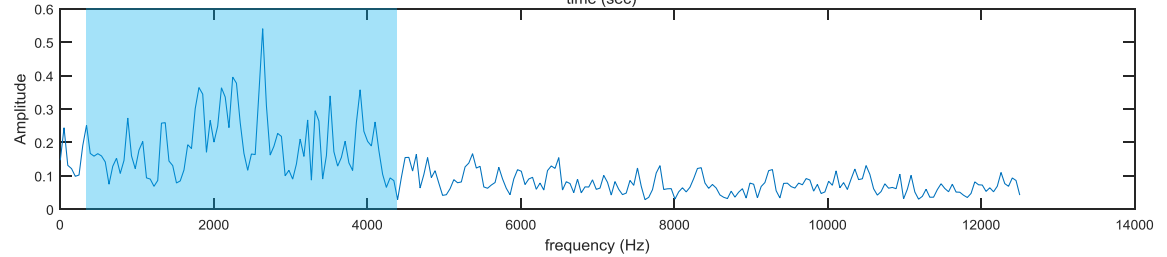
Temporal pixel fluctuations at $x/D_1 = 2$



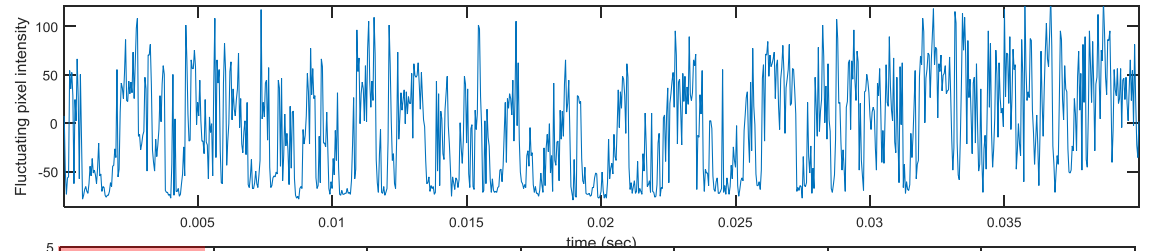
Time series



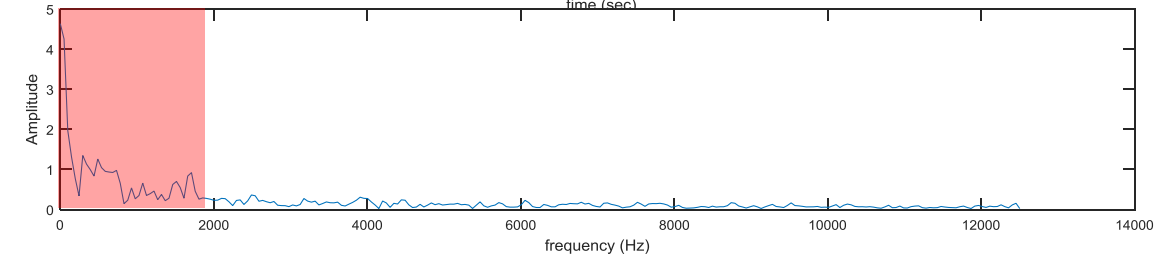
PSD



Time series



PSD



Shift of spectral content to lower frequencies



Linear Stability Considerations



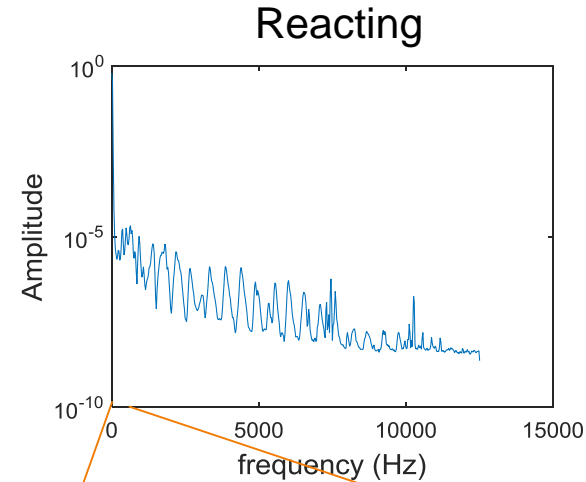
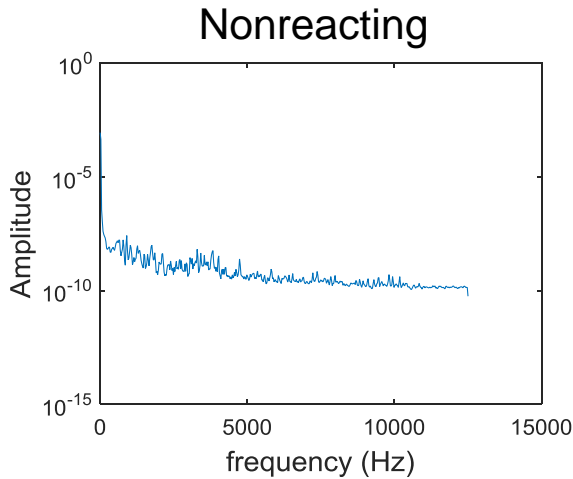
- **Mahalingam et al. (1991) predict a stabilization and shift to lower frequencies for a flame located in a jet shear layer**
- **Hajesfandiari and Forliti (2014) showed a similar trend for planar shear layers**
- **Furi et al. (2002) showed a damping effect of the flame on a shear layer, depending on the relative location of the flame within the vorticity profile**



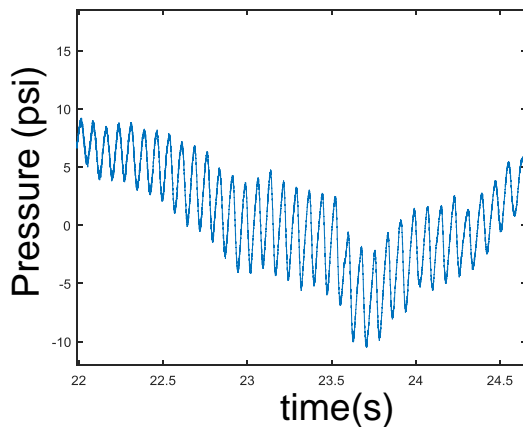
Chamber Acoustics, no Forcing



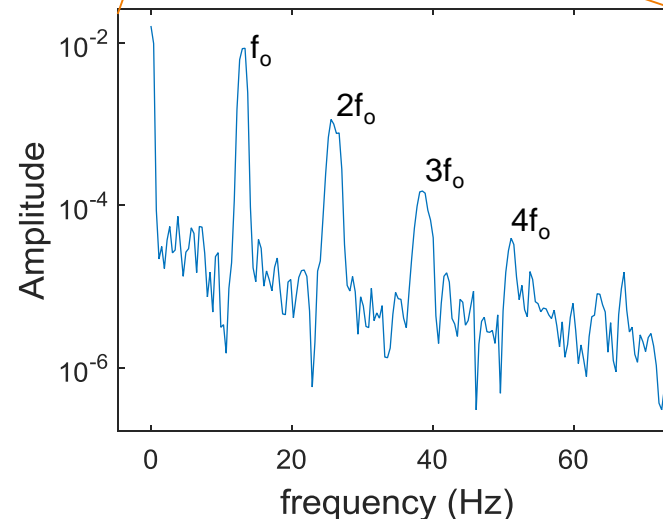
Spectra of chamber pressure fluctuations



13 Hz low frequency mode present for combustion. Control of this mode will be the subject of near-term research efforts.



Zoom in on low frequency





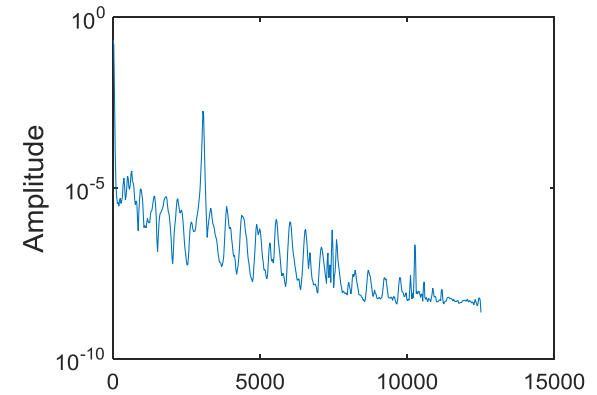
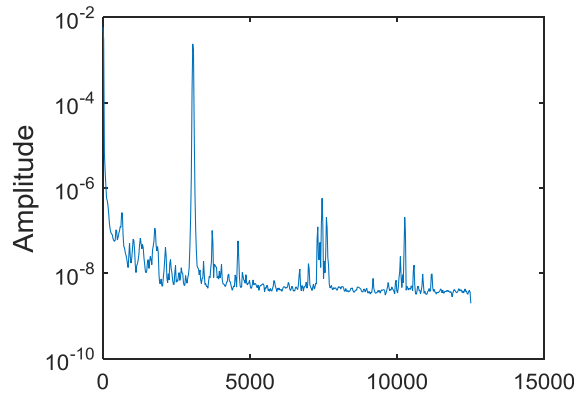
PAN Acoustic Forcing

Pressure antinode (PAN), forcing near 3000 Hz

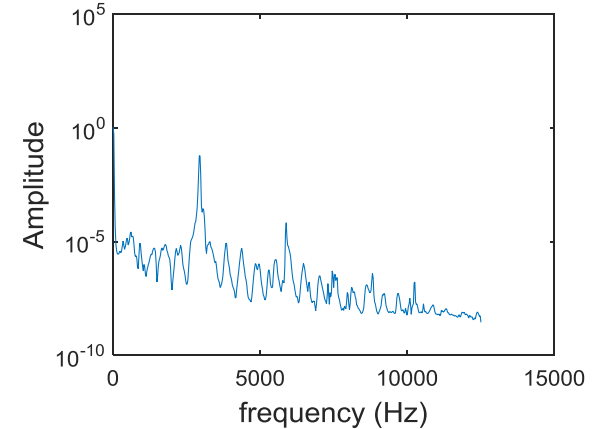
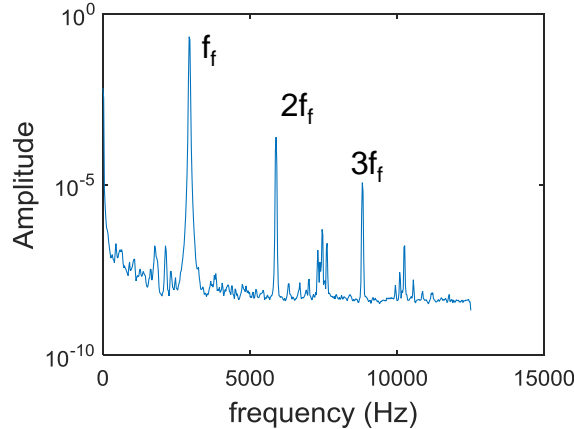
↓ Nonreacting

↓ Reacting

~ 1 PSIA



~ 5 PSIA



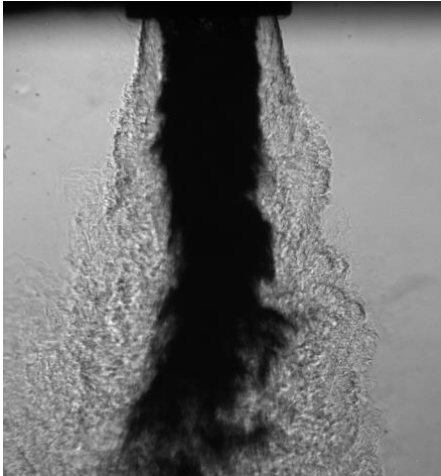


Acoustic Forcing Behavior

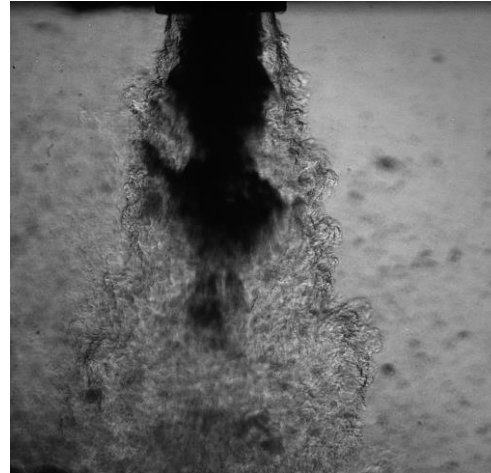


Nonreacting

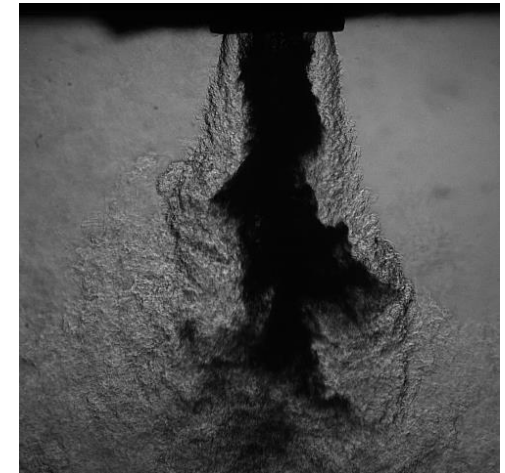
Unforced



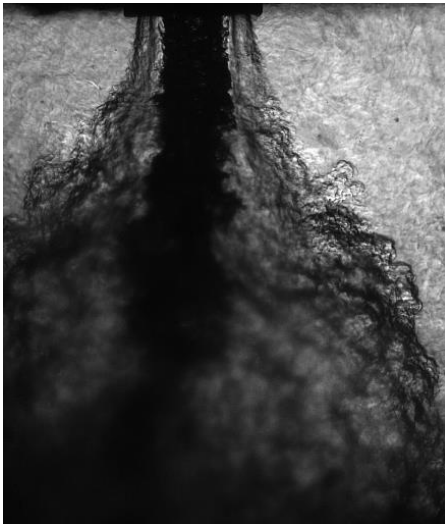
PAN Forcing



PN Forcing



Reacting



No evidence that acoustics affects flame holding



Dynamic Mode Decomposition



Extract spectrally-pure temporal modes with detailed spatial mode shapes

- Schmid (2010) and Rowley et al. (2009)
- Employ time-averaged amplitude measurement described by Alenius (2014)
- 1000-2000 sampled used

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

Amplitude of mode at $t = 0$

Time average image subtracted from data

Accounts for growth of mode in time as well as temporal frequency

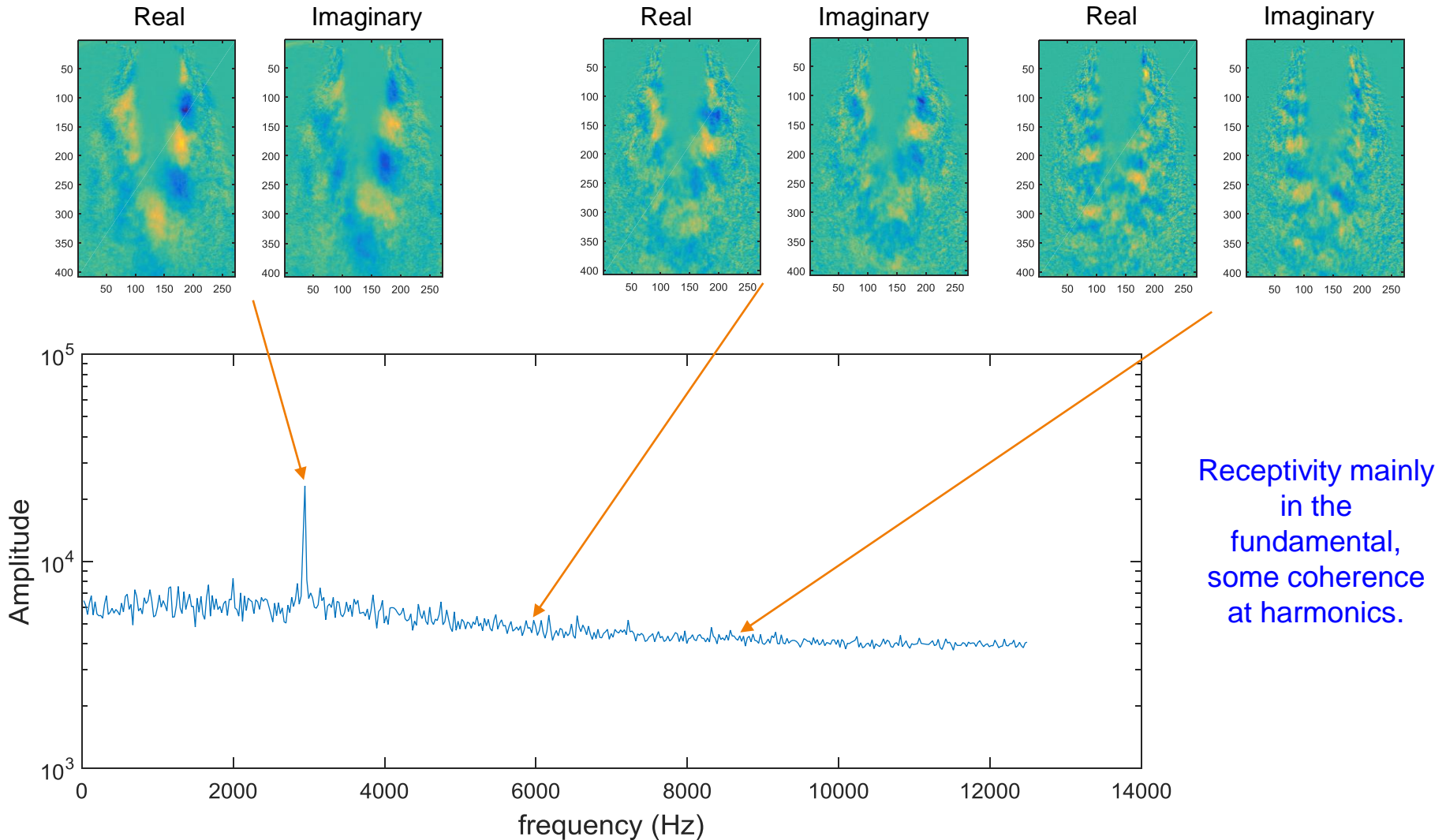
Complex spatial mode shape

Properties of DMD

- Isolates response of flow at forcing frequency and harmonics
- Single modes can reconstruct convective processes (POD requires two modes)
- Less efficient at reconstructing signal energy compared to POD

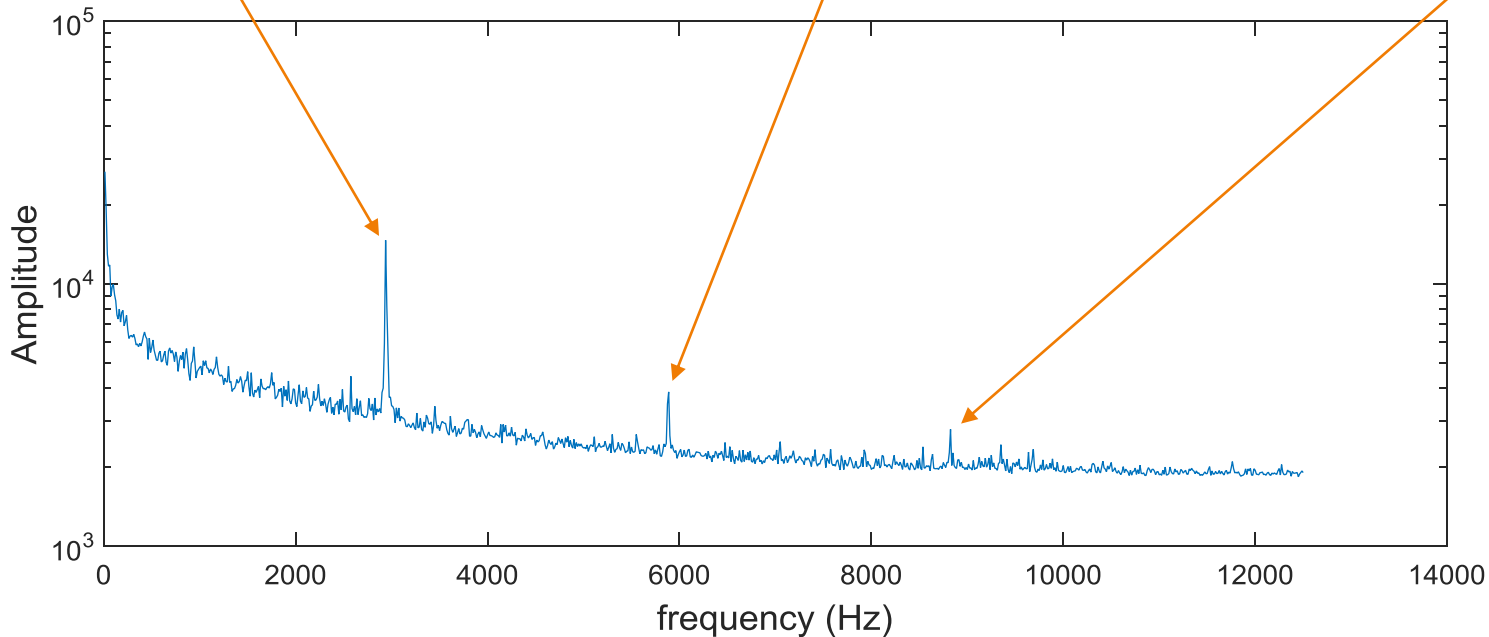
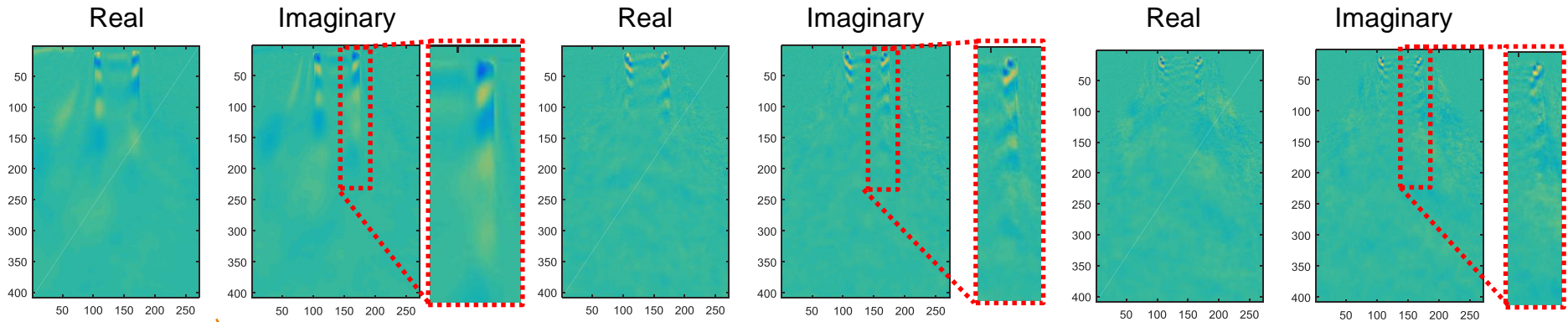


Max Forcing PAN: Nonreacting





Max Forcing PAN: Reacting

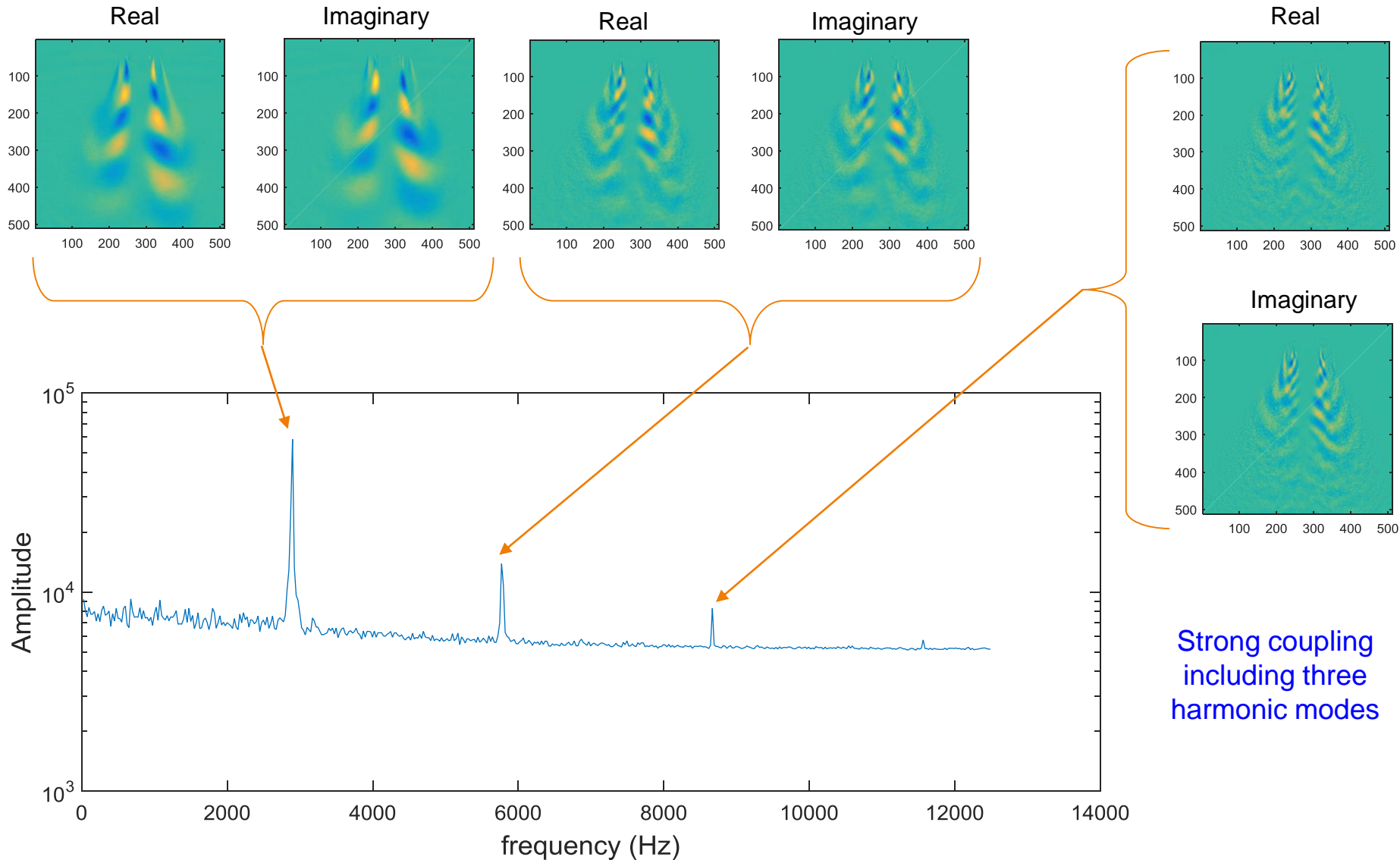


Receptivity of disturbances (fundamental and harmonics) in the shear layer.

Positive Global Rayleigh Index was calculated using a photomultiplier for OH emissions.



Max Forcing PN: Nonreacting



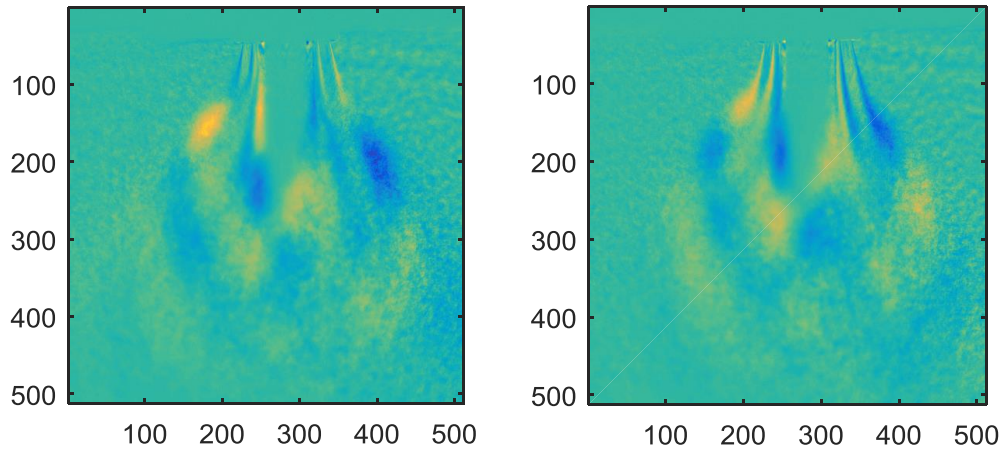


Max Forcing PN: Reacting



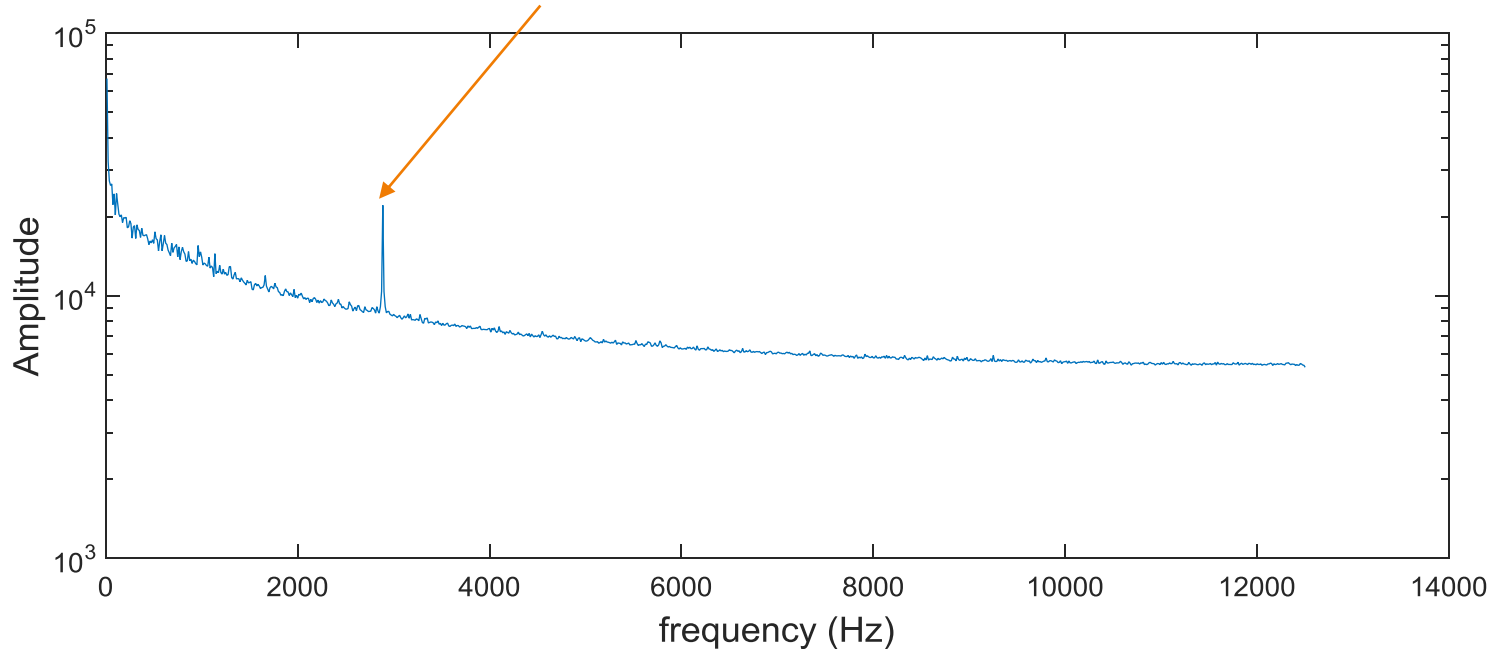
Real

Imaginary



Antisymmetric structure
with coherent coupling
between the outer and
inner shear layers.

Global Rayleigh Index
was also positive.

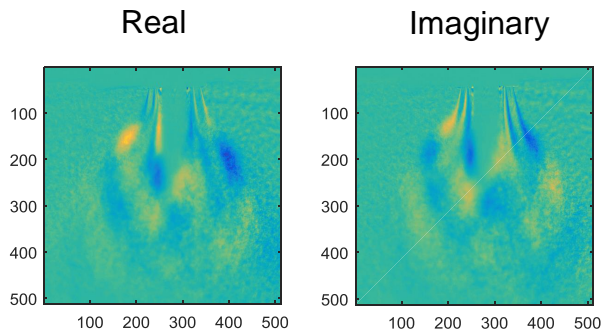




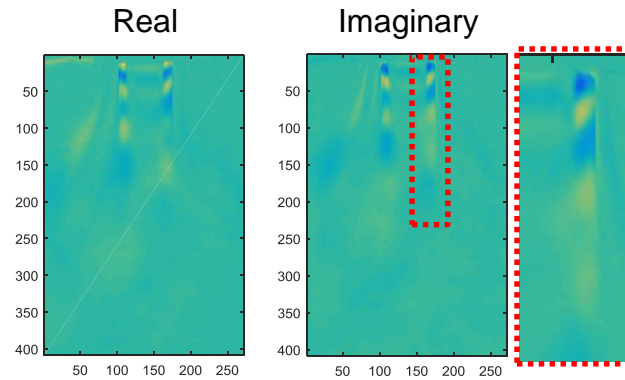
Max Forcing: Reacting



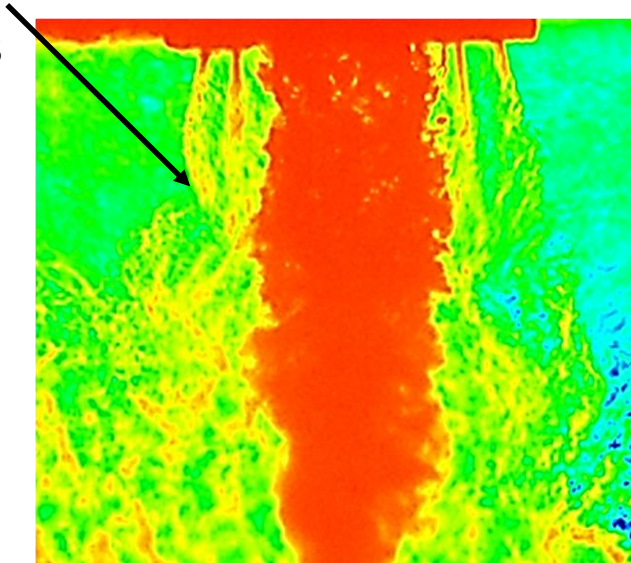
PN Forcing



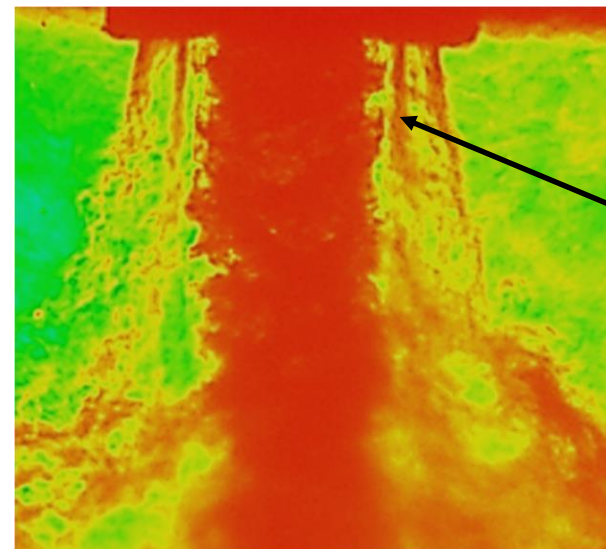
PAN Forcing



Outer GH2
Jet responds
to acoustic
forcing



LOX Core
responds to
acoustic
forcing





Conclusions, unforced



- **A blurred interface between the GH2 and LOX appears to be in the fibrous atomization regime.**
- **Reactions cause a significantly more expanded plume due to the vaporization and expansion of the LOX.**
- **A LOX recirculation zone was unexpectedly dominant.**
- **Flameholding is established at the lip, consistent with the observations of others.**
- **Unreacting convective structures propagate downstream at relatively constant velocity.**
- **Reacting structures start at slow speed and gradually accelerate with downstream distance, but never reach the velocity of nonreacting structures.**
- **Reactions shift the spectral content to lower frequencies, consistent with trends observed in the linear stability literature.**



Conclusions, forced



- **Acoustics do not appear to affect the flameholding.**
- **The GH₂/LOX interface is not blurred as nonreacting case instead larger ligaments and droplets are observed to shed.**
- **The shed ligaments and droplet shed within 1 LOX diameter get entrained into the LOX post recirculation zone.**
- **Dynamic mode decomposition detects jet response not only at the fundamental frequency but at higher harmonics.**
- **Reactions produce inconsistent trends in the harmonics:**
 - Reactions promote harmonics at a pressure antinode.
 - Reactions damp harmonics at a pressure node.
- **Flame seems to providing a shielding effect on the LOX core.**
- **Cold flow results predict a wide range of responses when conditions are varied over wider ranges.**



Future Work



- **Mitigation of 13 Hz mode.**
- **Rayleigh index diagrams to indicate whether response is driving or damping.**
- **Variation of parameters over a broader range, guided in part by linear stability theory.**
- **Three-element interactions.**

