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Dynamics of High Pressure Reacting Shear Flows

Space Power and Propulsion Contractor's Meeting

2 October 2015

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

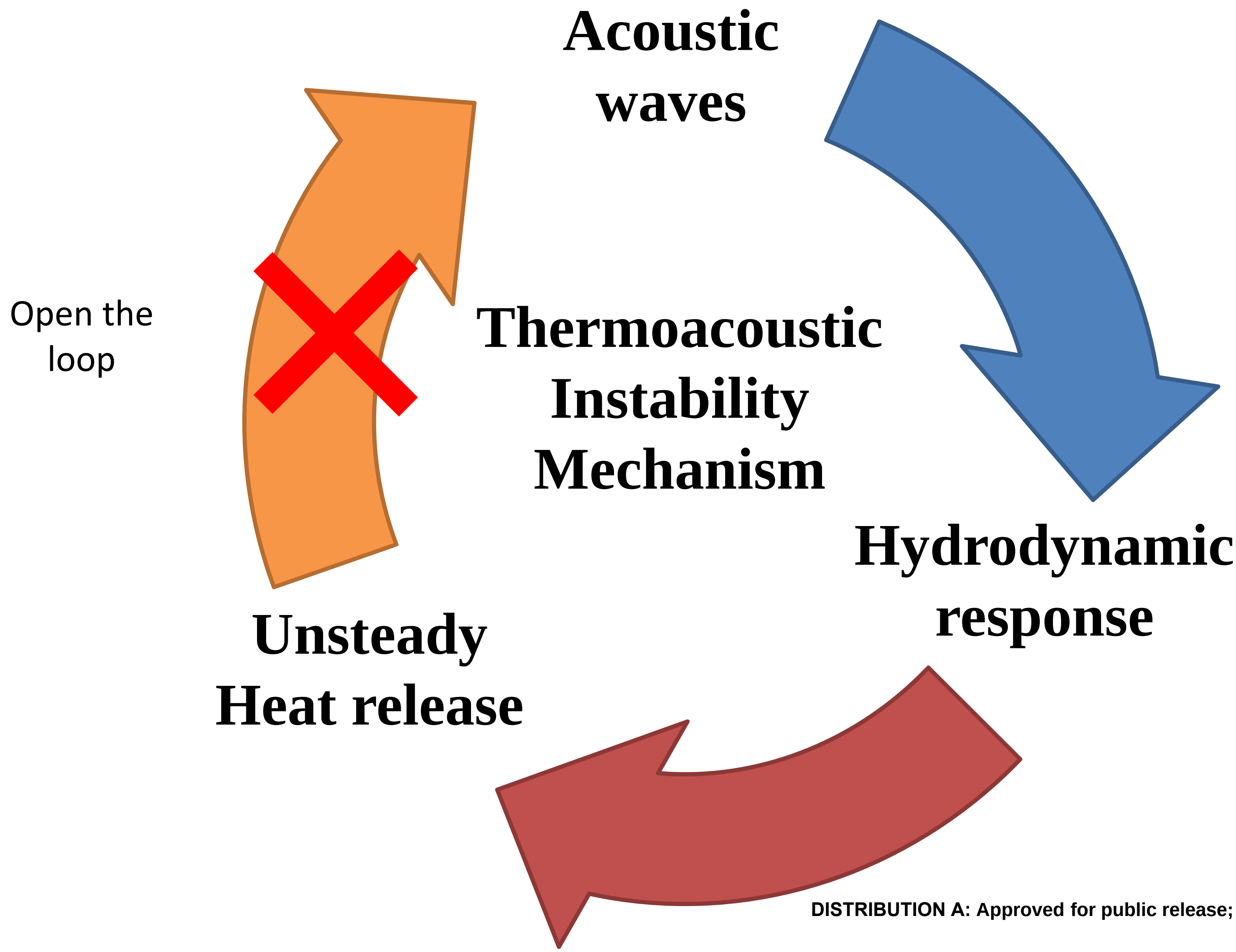
AF relevant considerations

- **Achieving modern thermodynamic efficiencies requires achieving increasingly higher chamber pressures, sometimes exceeding the critical pressure of the reactants**
  - 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
- **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**
  - eg, combustion instabilities

Objectives

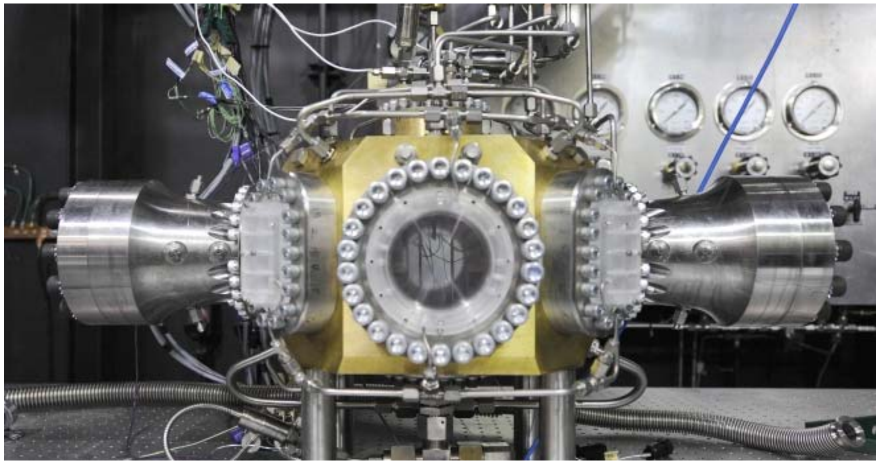
- **Determine the mechanisms governing the dynamics of a high pressure, chemically reacting, multiphase, acoustically driven, shear flow in the form of a coaxial jet flame**
- **Explore how the presence of chemical reactions affects the response of coaxial jets to acoustic forcing.**
- **Explore inter-element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

Approach



Acoustic waves
Hydrodynamic response
Unsteady Heat release
Thermoacoustic Instability Mechanism
Open the loop

Experimental Facility



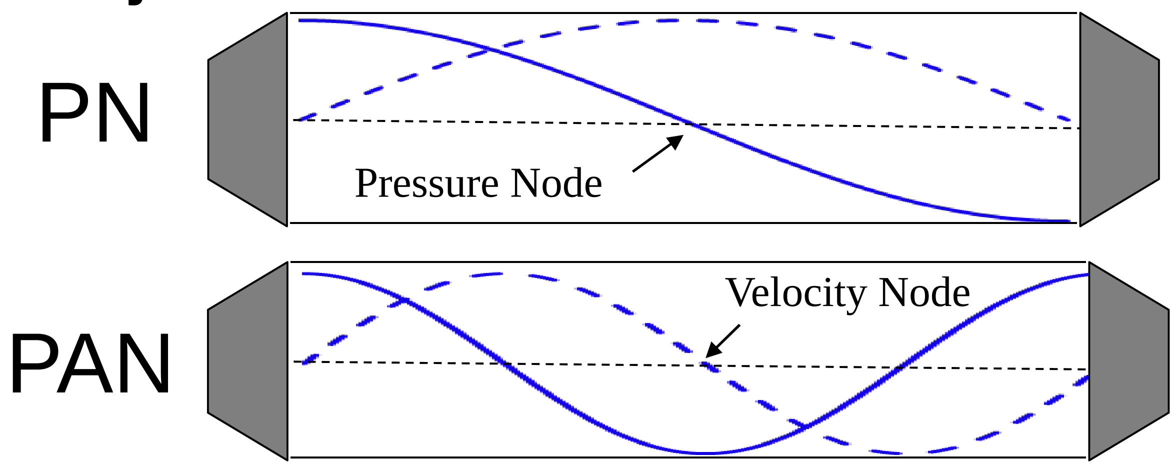
Features

- 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

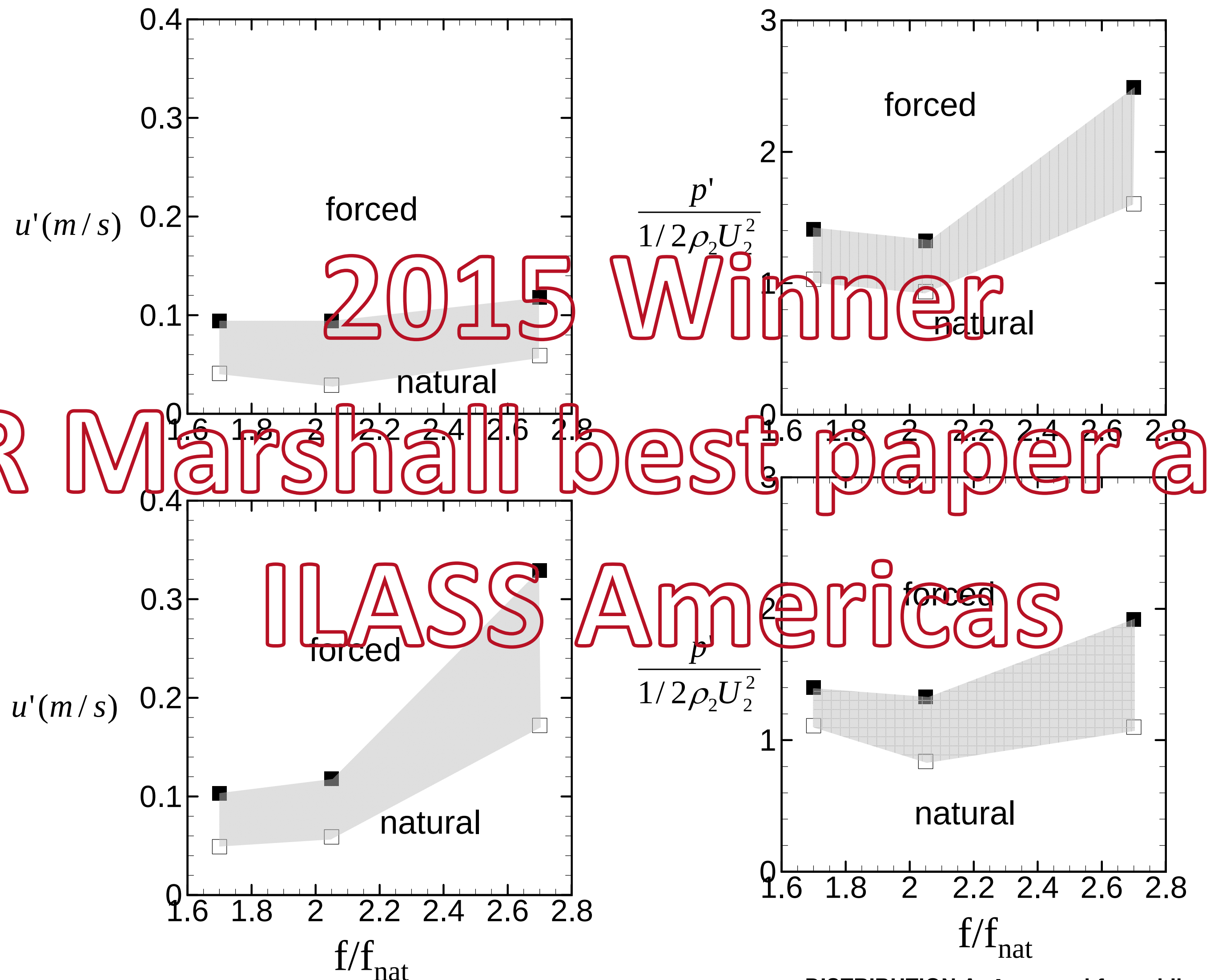
- **Forcing frequency ~ 3000 kHz**
- **Pressure fluctuation amplitudes (peak-to-peak) range up to approximately 9 psi (6 psi reacting)**

Cold Flow Update

Pressure node **Pressure antinode**

J = 2

J = 6



2015 Winner

WR Marshall best paper award

ILASS Americas

Receptivity LN2 / GHe jets

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2015 Developments

- **Added direct measurement of the pressure field**
  – High speed pressure transducers damaged in 2014, forcing use of piezoceramic voltage as indirect measure of relative amplitude and no measurement of phase.
- **Damaged image intensifier has precluded OH chemiluminescence measurements**
  – Repairs expected in the fall
- **Shadowgraph optics was significantly improved**
- **Liquid hydrocarbon capability was installed under another program**

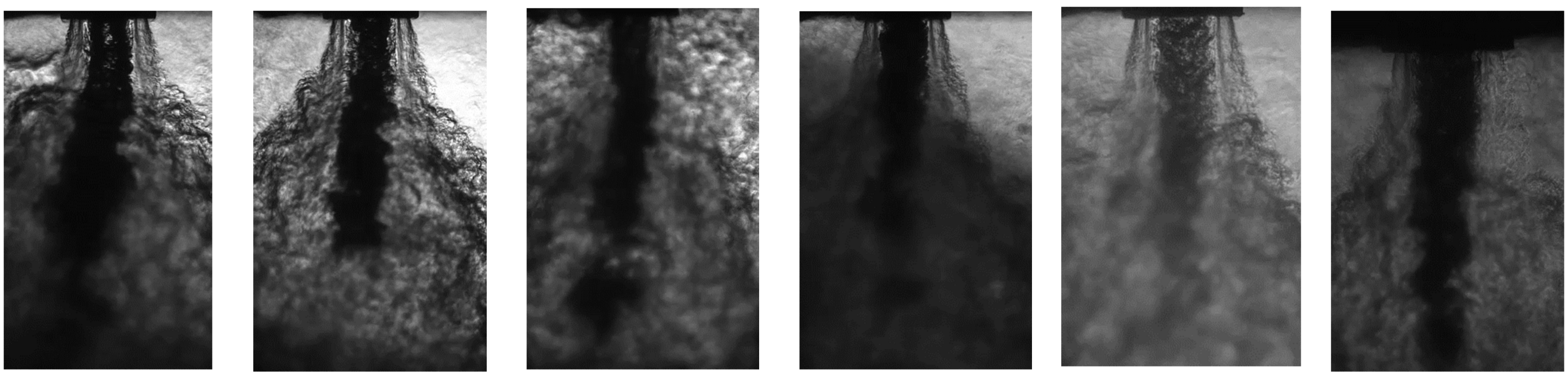
Forced Flames

2014 results *used acoustic driver voltage as measure of forcing amplitude*

V’ → 0 V | 0.5 V | 1.0 V | 1.5 V | 2.0 V | 2.5 V

New results *with characterized acoustic forcing amplitude—key to physics understanding*

P’ → 0 psi | 1.5 psi | 2 psi | 3.5 psi | 5.3 psi | 5.5 psi

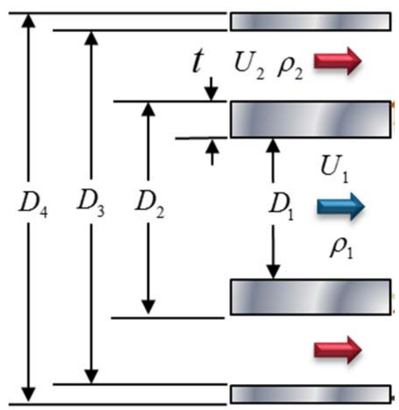


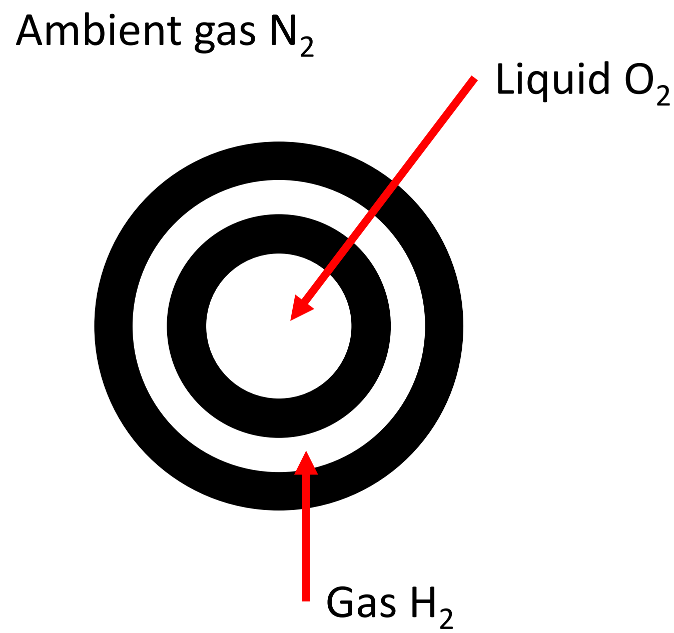
Pressure measurements synchronized to chemiluminescence → Rayleigh Index imaging

Spatial pressure measurements → direct measurement of acoustic mode

Operating Conditions

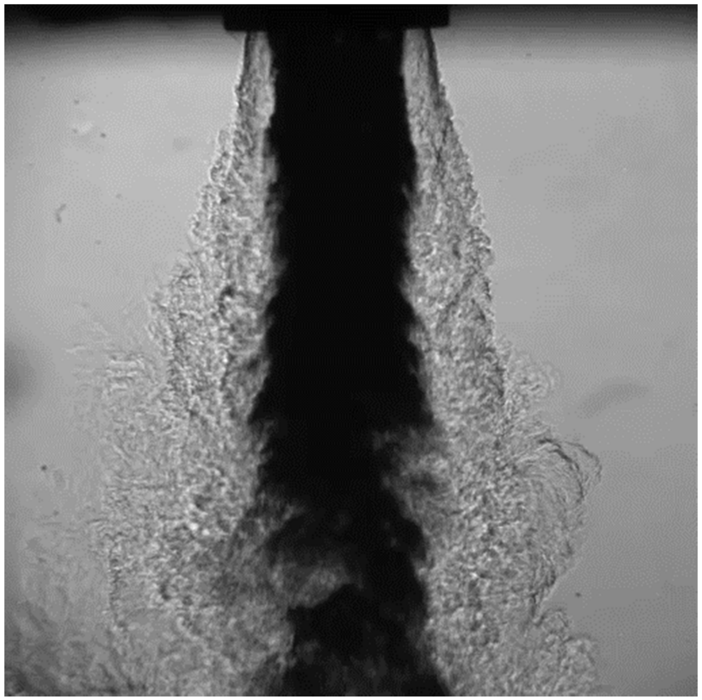
- **Cryogenic liquid O_2 and gaseous H_2 flame**
- **Injector geometry**
  - D$_1$ = 1.4 mm
  - AR = 1.68
  - t/D$_1$ = 0.27
- **J ≈ 2.2**
- **MR ≈ 6-7**
- **O_2 inner jet @ 140 K**
- **H_2 outer jet @ 250 K**
- **Fully-developed turbulent flow conditions**
- **Chamber pressure 3.4 MPa (500 psi)→ subcritical**



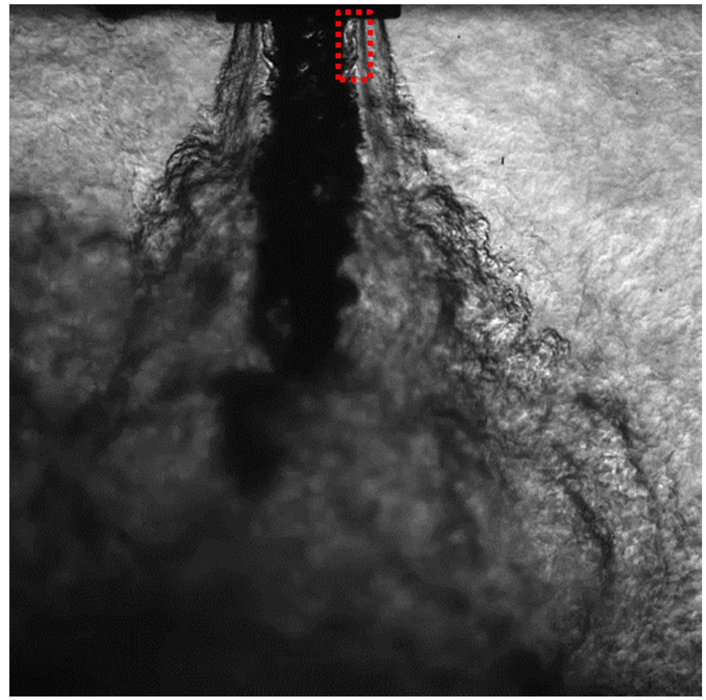


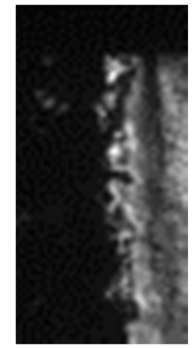
Unforced Results

Nonreacting



Reacting



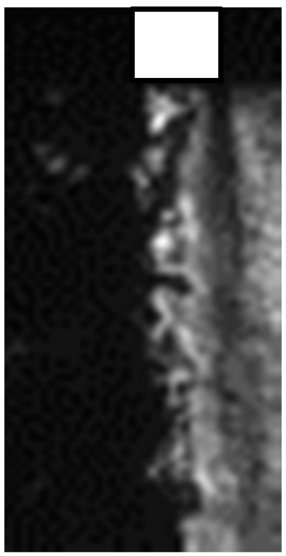


Differences:

- 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

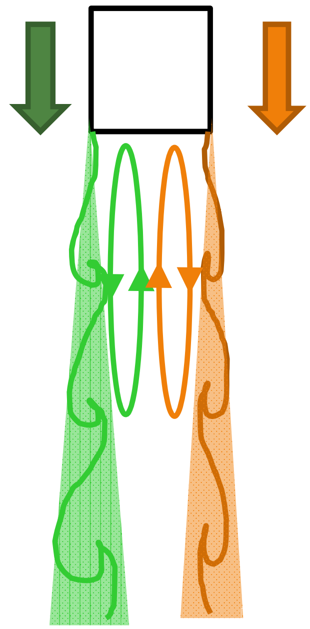
Recirculation Zone Phenomenon

Combustion case



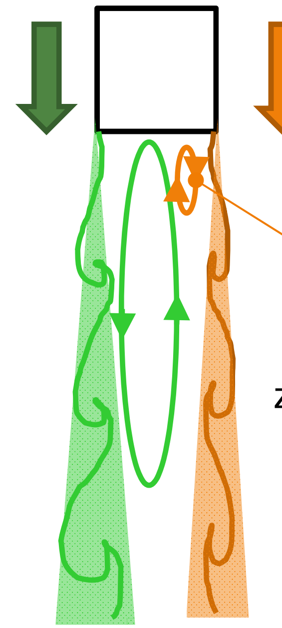
Symmetric recirculation zones

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

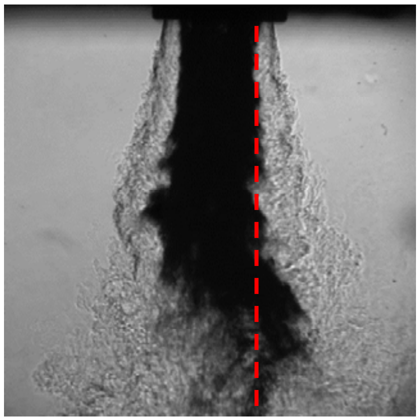
Results show large oxygen-side recirculation zone that brings liquid O_2 structures very close to hydrogen shear layer.

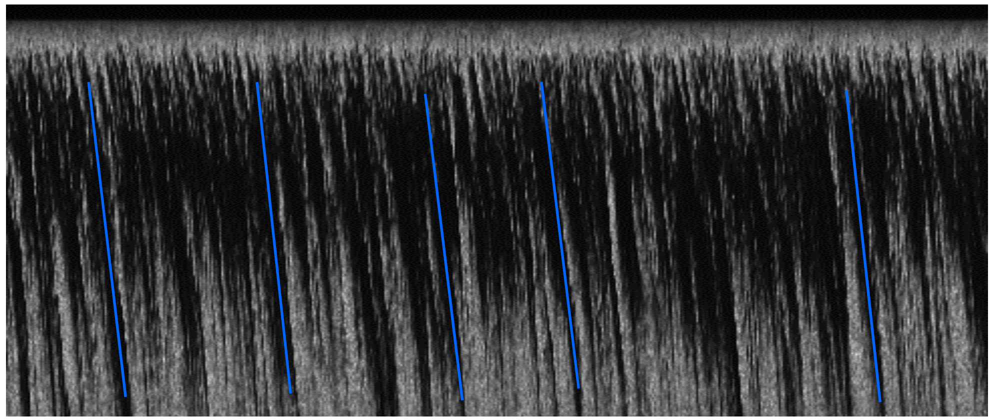
Convection Velocities

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

x

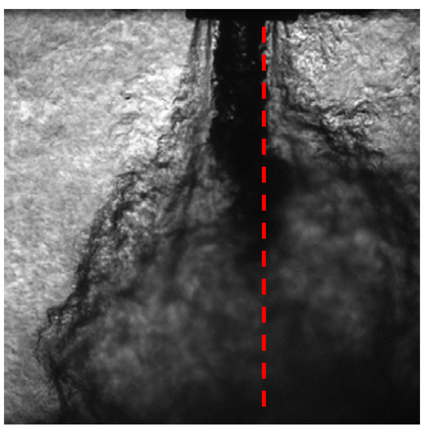
y

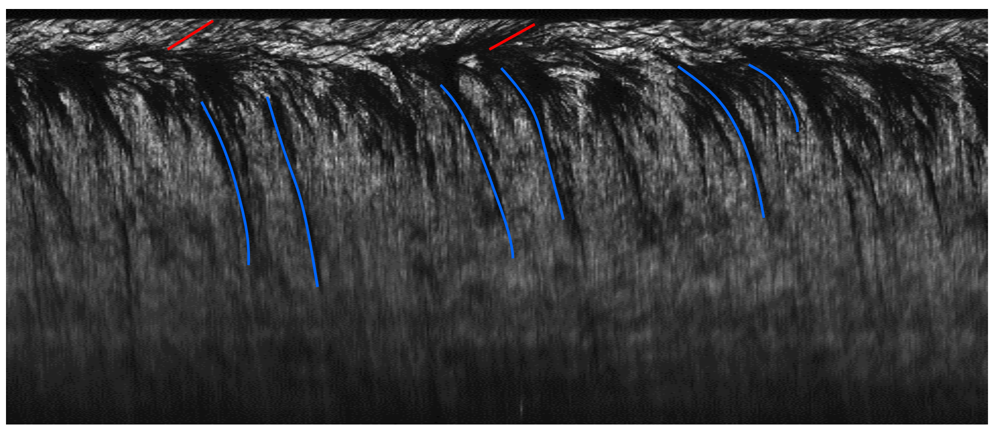




time

Structures convect at apparent constant velocity



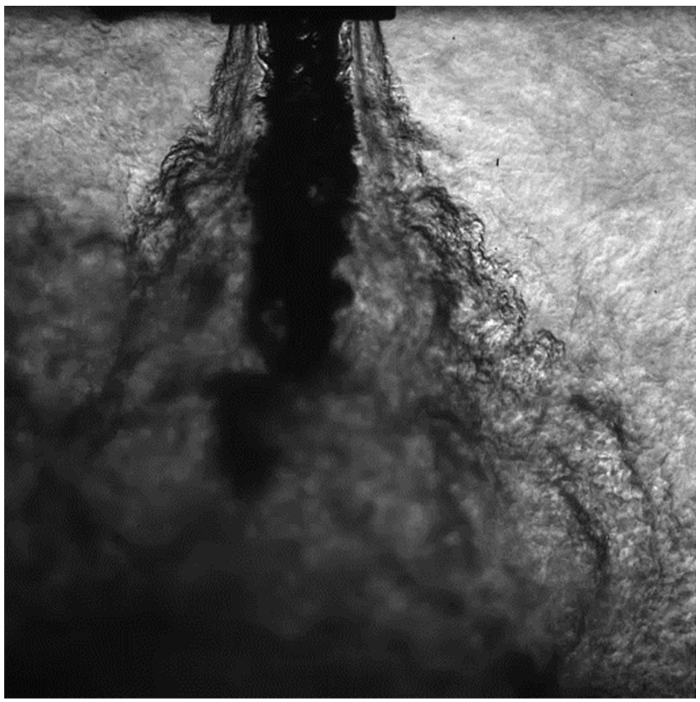


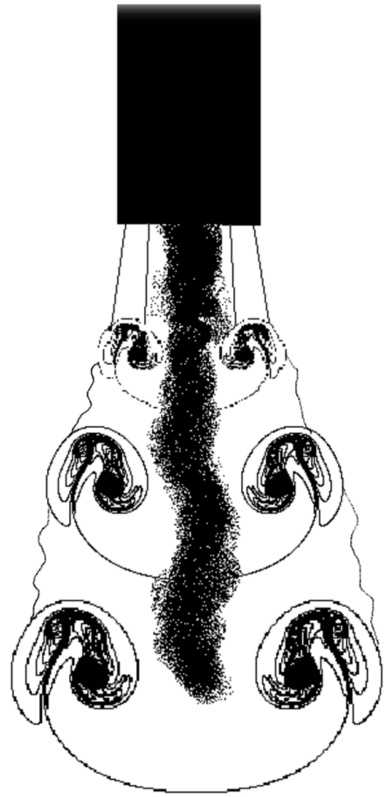
time

Positive slope streaks represent upstream traveling features

Structures start at slow speed and gradually accelerate with downstream distance

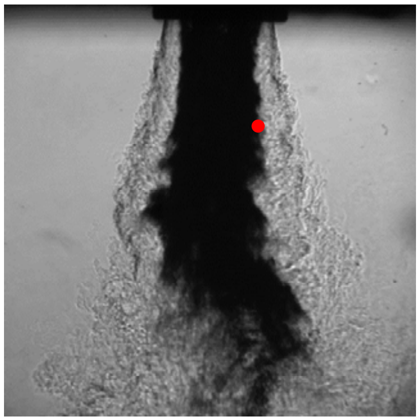
Downstream combustion structures



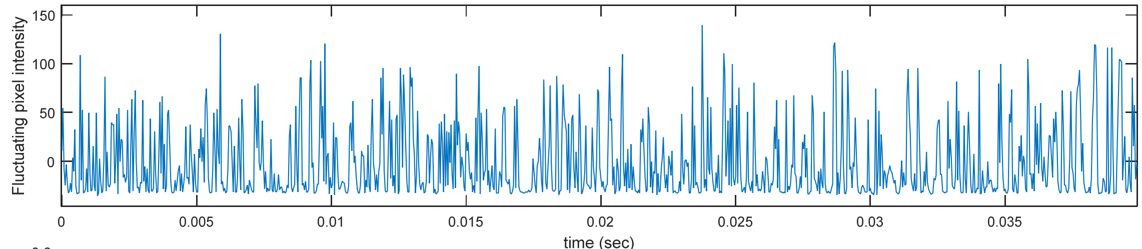


Near Field Shear Layer Dynamics

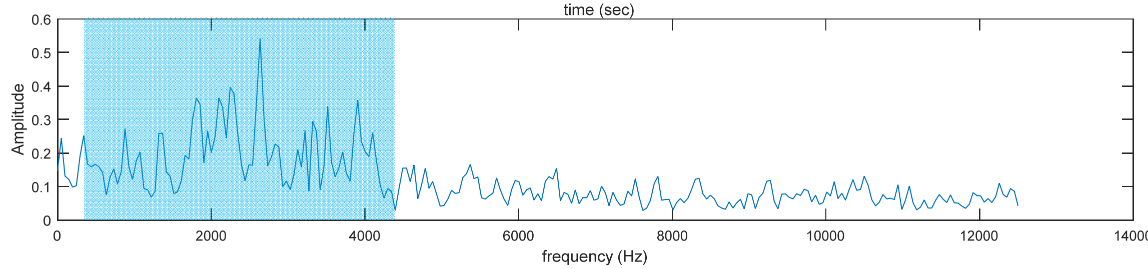
Temporal pixel fluctuations at $x/D_1 = 2$

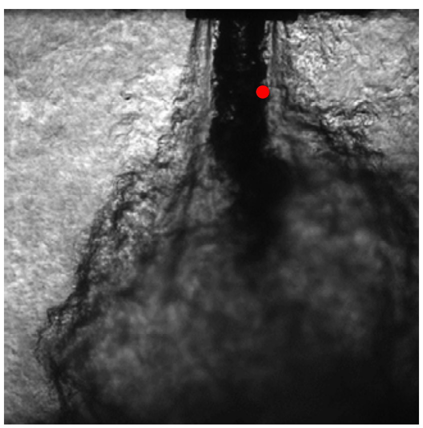


Time series

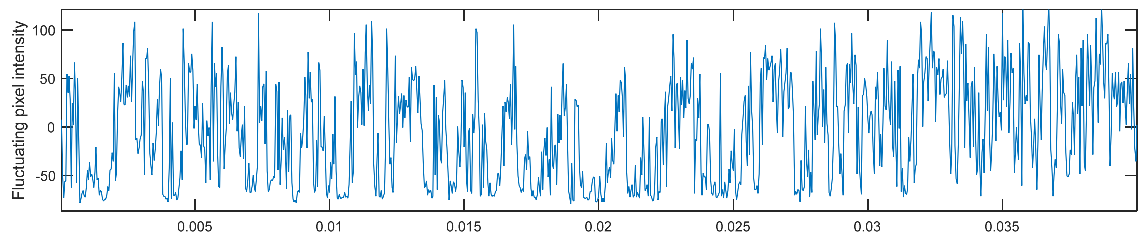


PSD

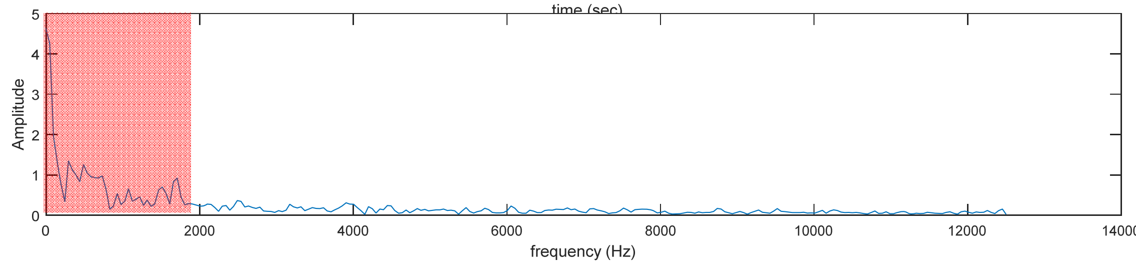




Time series



PSD



Shift of spectral content to lower frequencies—trend seen in 2014 for chemiluminescence-based data

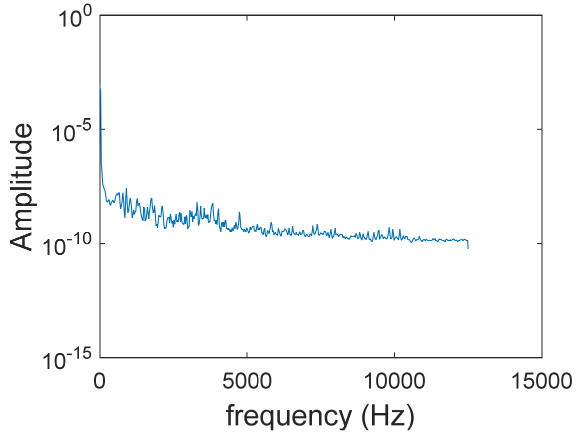
Linear Stability Considerations

- 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

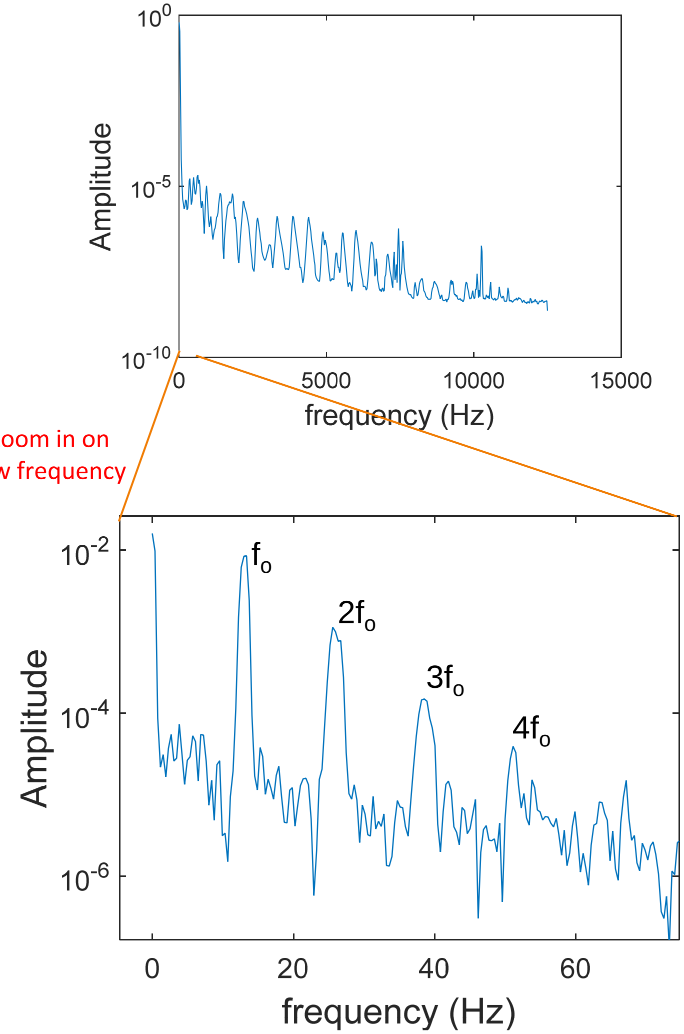
Chamber Acoustics, no Forcing

Spectra of chamber pressure fluctuations

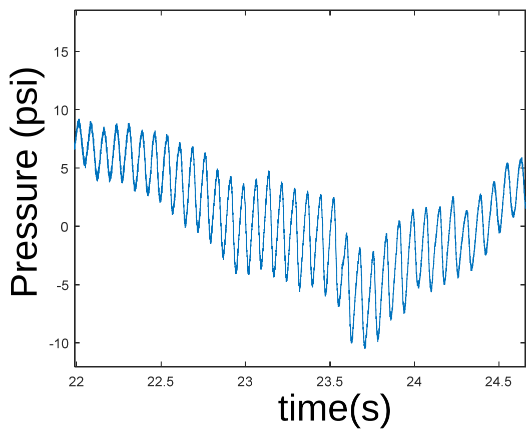
Nonreacting



Reacting



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



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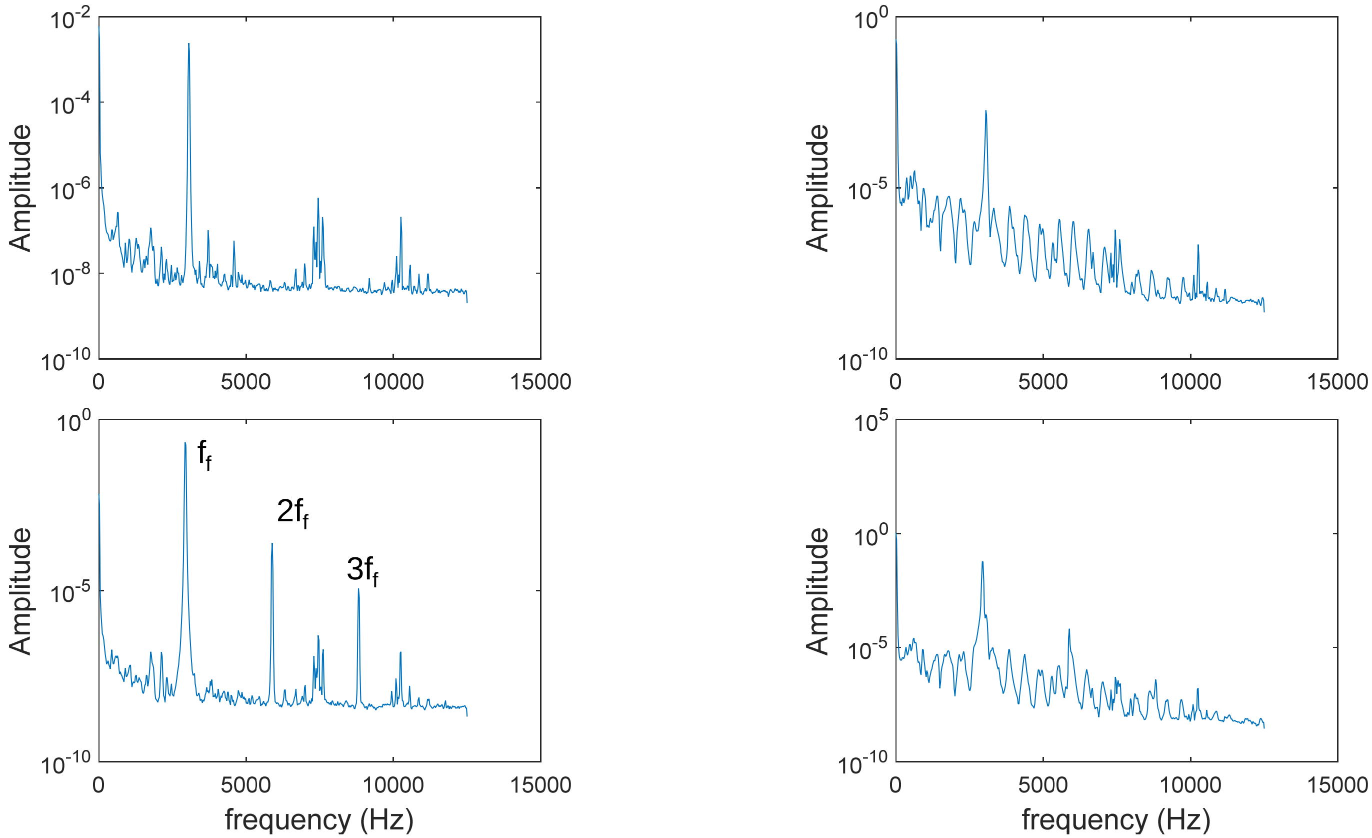
PAN Acoustic Forcing

Pressure antinode (PAN), forcing near 3000 Hz

Nonreacting | Reacting

~ 1 PSIA

~ 5 PSIA

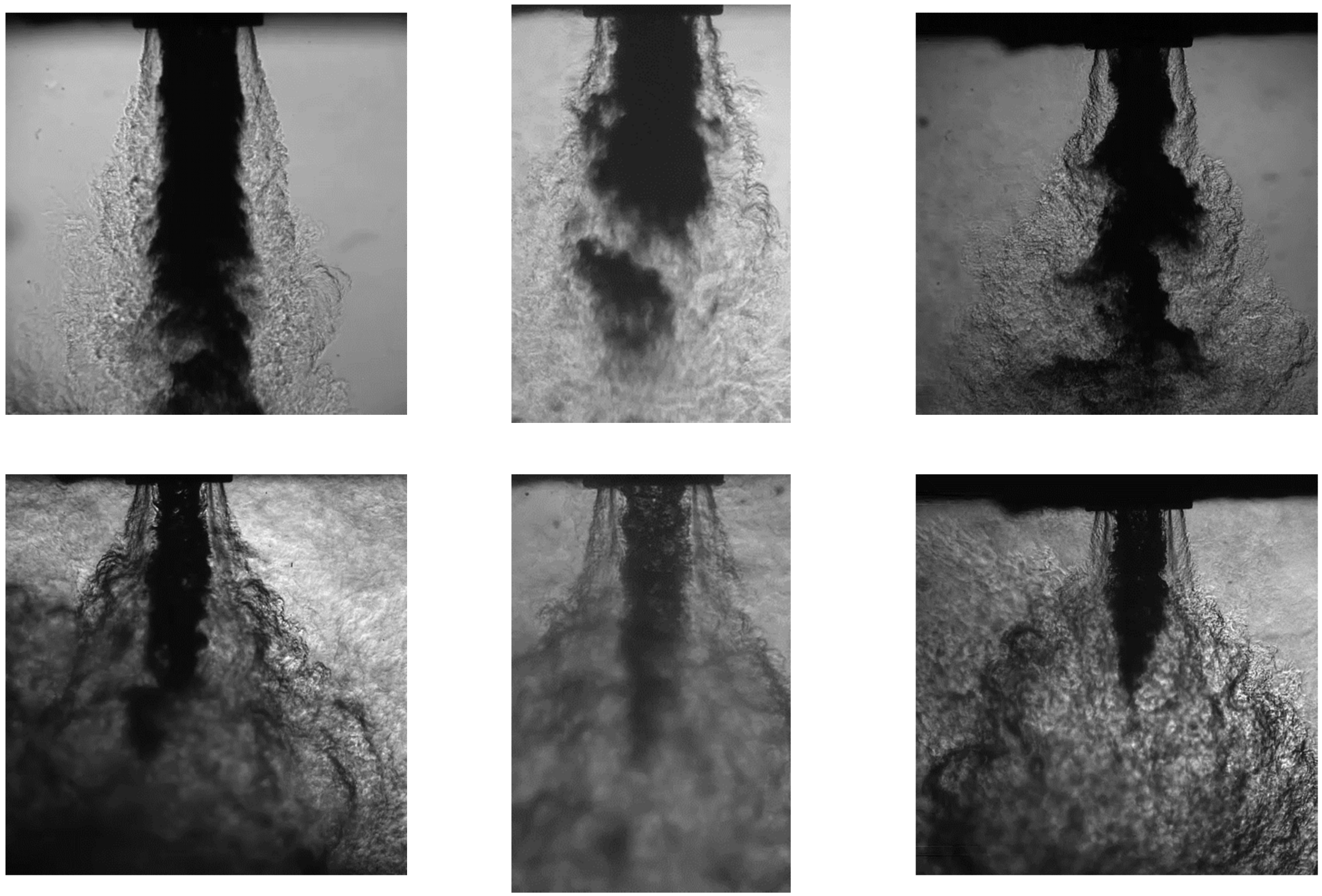


Acoustic Forcing Behavior

Unforced | PAN Forcing | PN Forcing

Nonreacting

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

Amplitude of mode at t = 0

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

Time average image subtracted from data

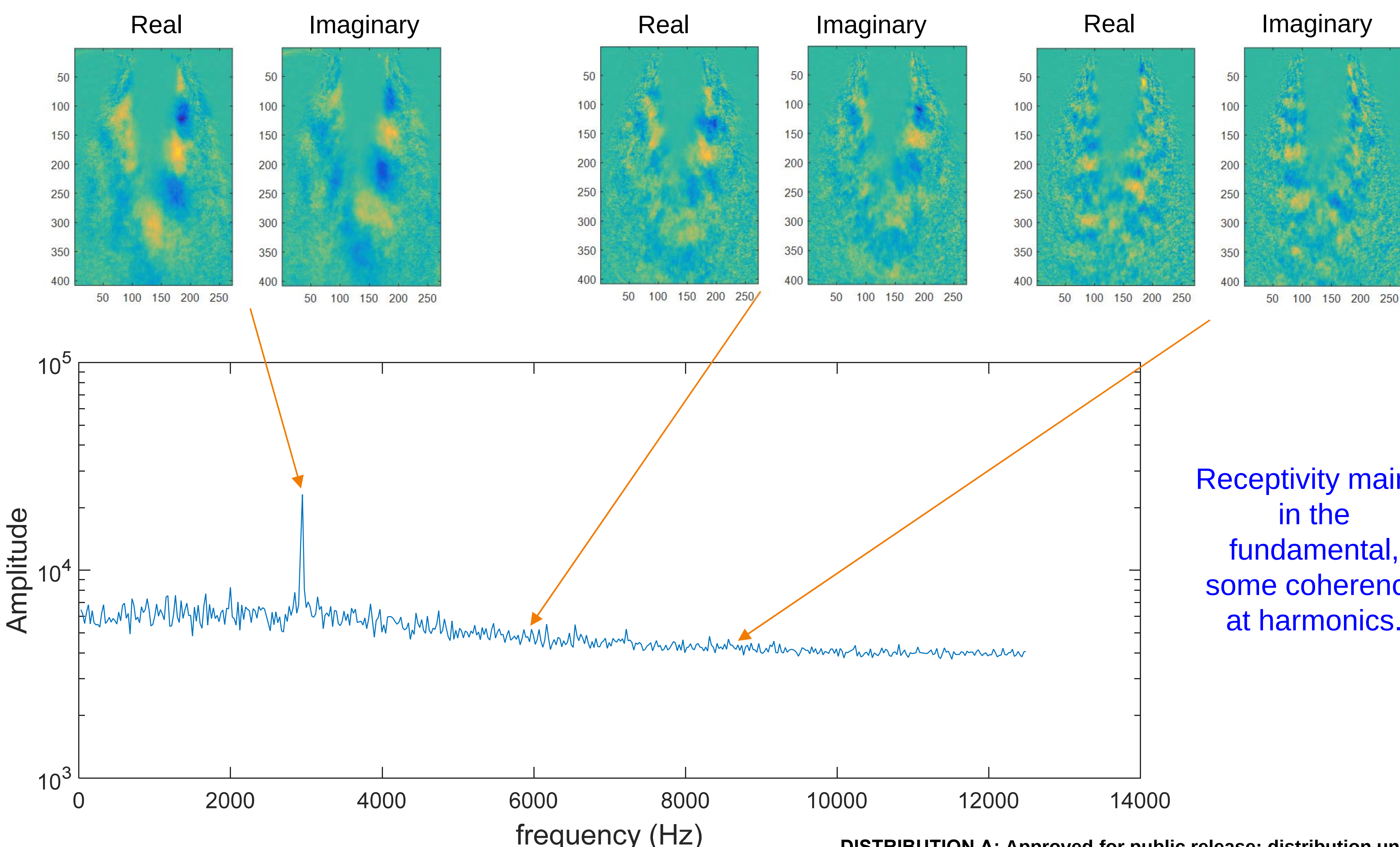
Accounts for growth of mode in time as well as temporal frequency

Complex spatial mode shape

Properties of DMD

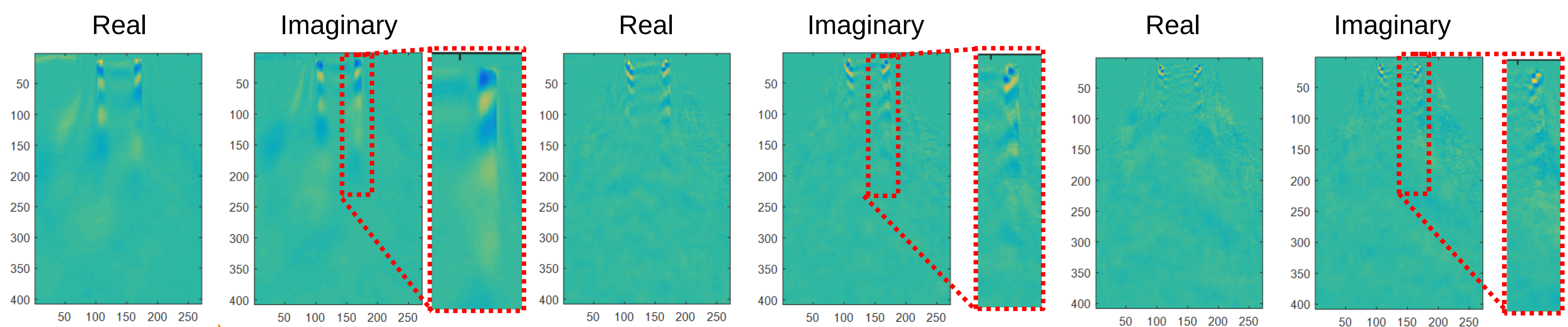
- Isolates response of flow at forcing frequency and harmonics
- Single modes can reconstruct convective processes (POD requires two modes)
- Less efficient at reconstructing signal energy compared to POD

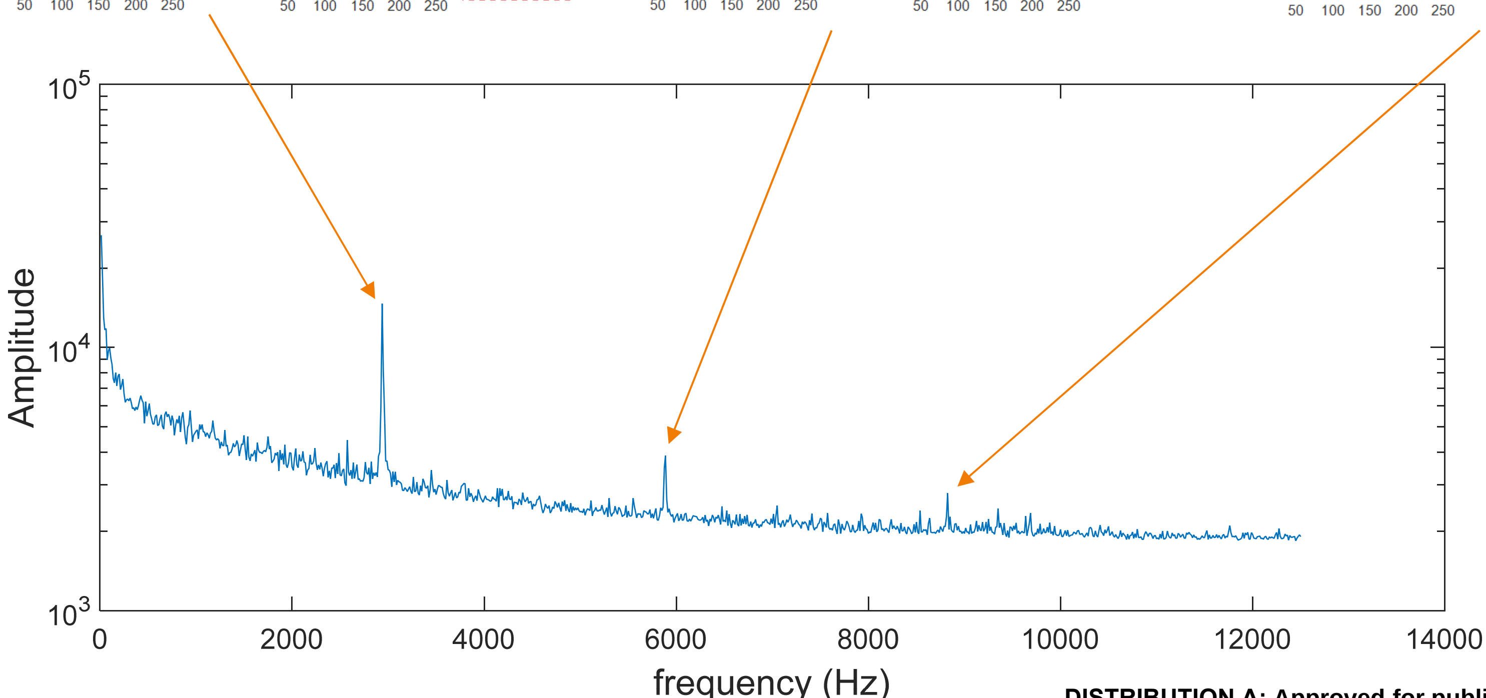
Max Forcing PAN: Nonreacting



Receptivity mainly in the fundamental, some coherence at harmonics.

Max Forcing PAN: Reacting

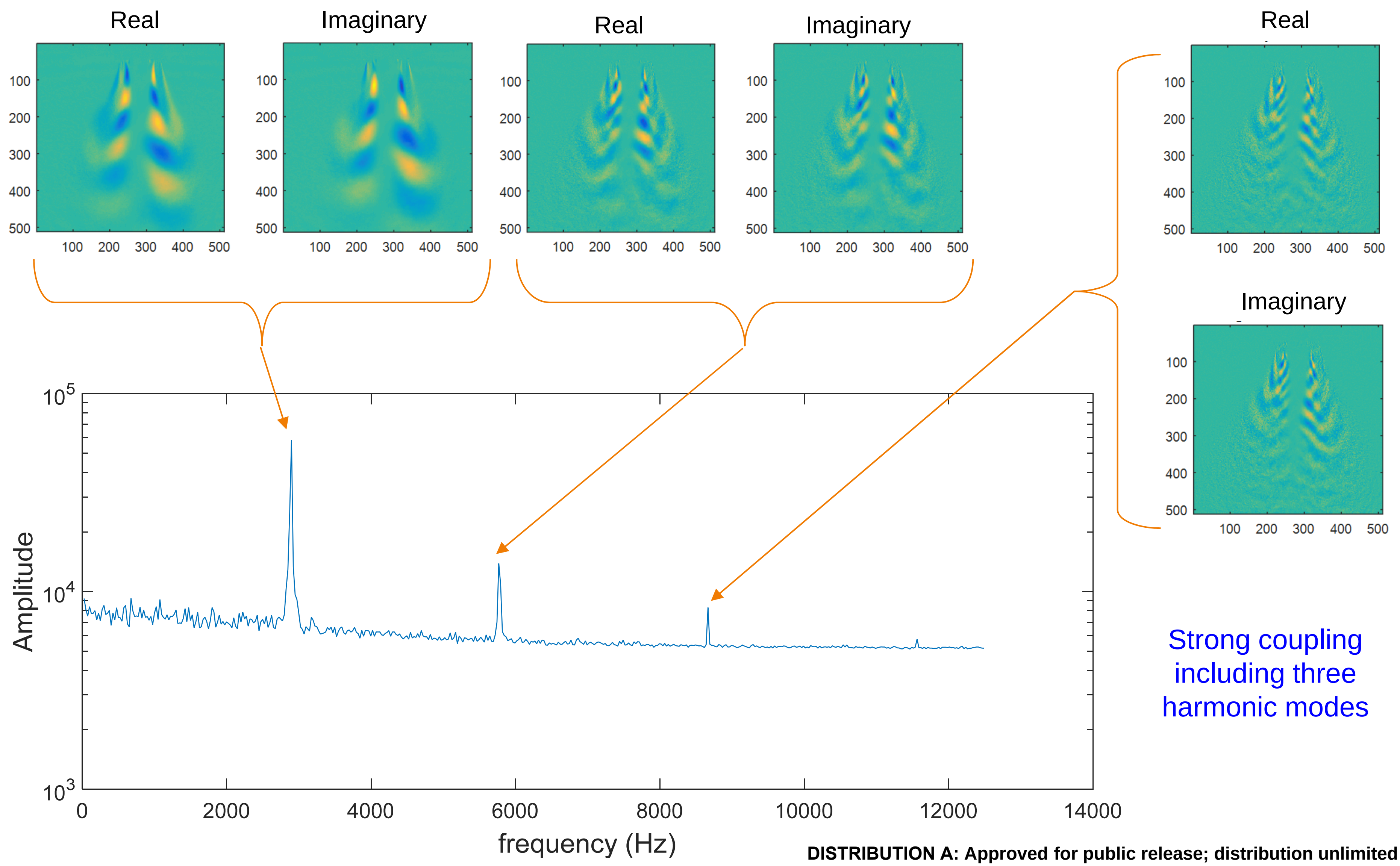




Receptivity of disturbances (fundamental and harmonics) in the shear layer.

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

Max Forcing PN: Nonreacting



Strong coupling including three harmonic modes

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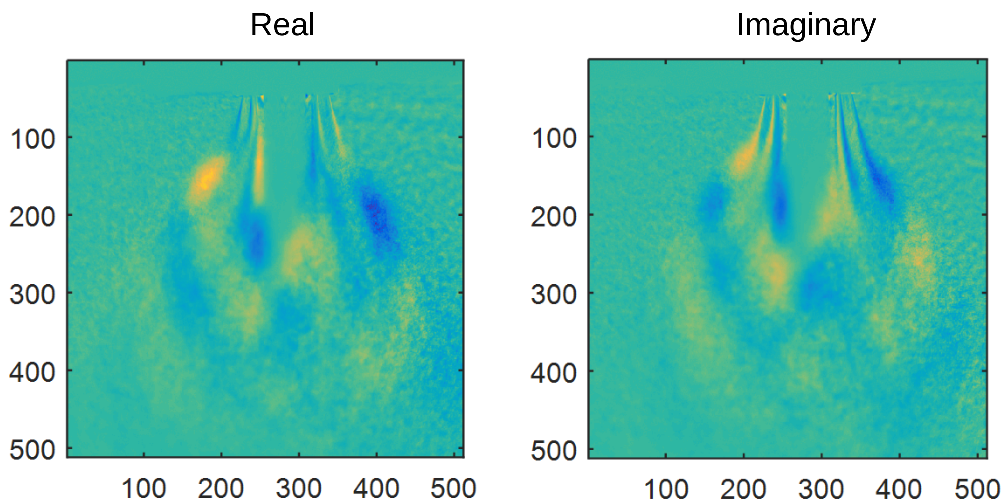
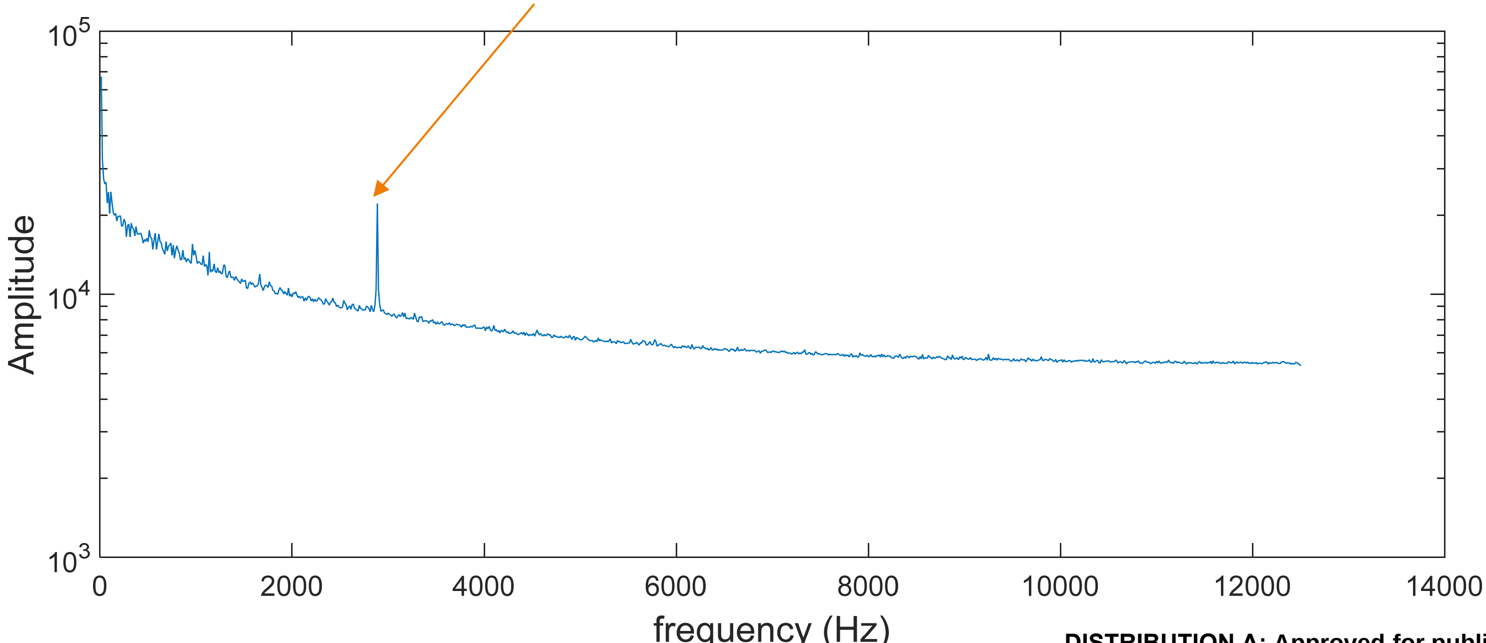
Max Forcing PN: Reacting



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

Global Rayleigh Index was also positive.



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Conclusions, unforced

- **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.**
- **A 13 Hz mode is present, but is significantly slower than the high frequency measurements**

Conclusions, forced

- **Acoustics do not appear to affect the flameholding**
- **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.
- **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.

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