Interpretation of Period Doubling Bifurcation in Thermoacoustically Unstable Combustion of Propane

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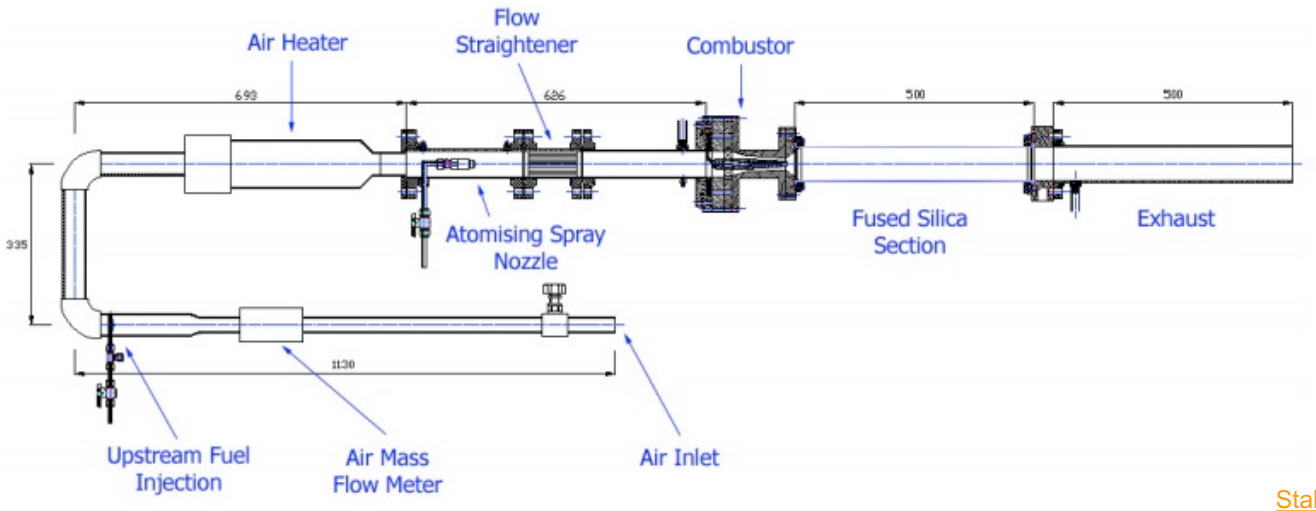
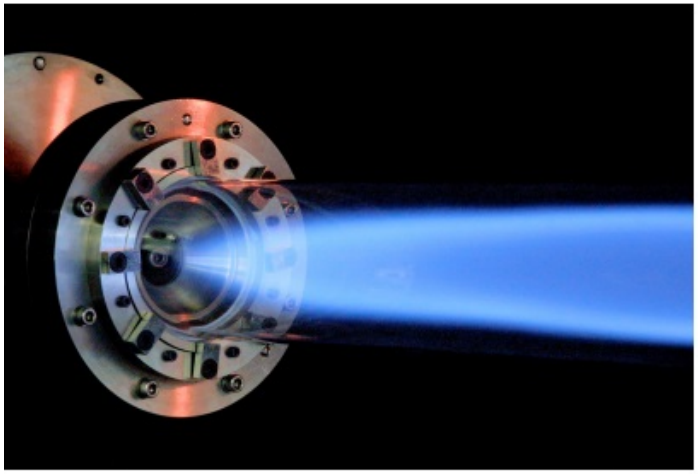
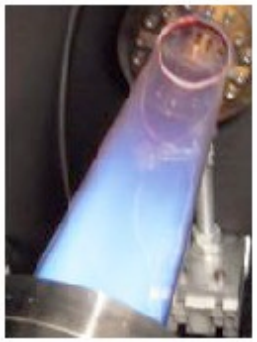
Model Gas Turbine Combustor Geometry





Stable | Intermittent | Oscillatory





Characteristics

- Swirl premixed stabilized combustor.
- Swirl number is approximately 0.7.
- Flow field is fully turbulent, as Reynolds numbers up to 30000 can be examined.
- Equivalence ratios examined in the current campaign span from 0.50 to 0.70.

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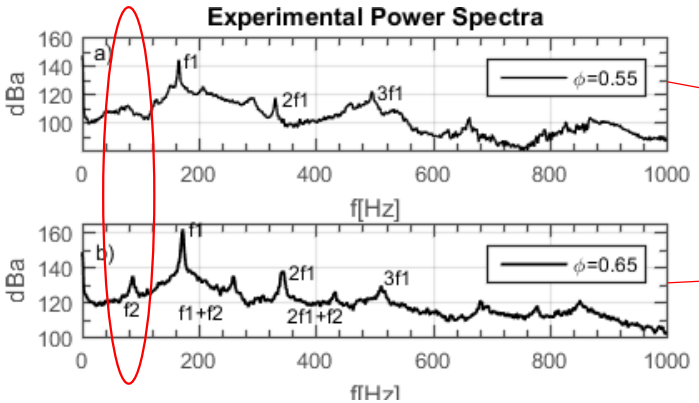
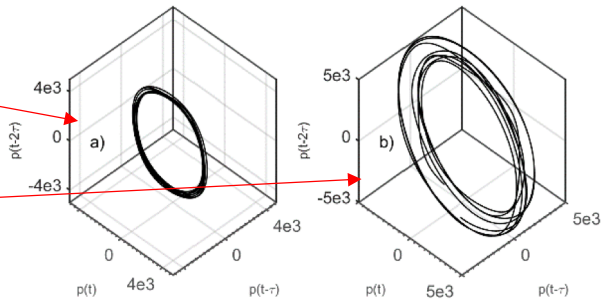
Problem Outline: On increasing equivalence ratio dynamics bifurcate from Period 1 to Period 2 state



Phase Space Reconstruction of Dynamic Pressure



Linear Acoustic Model to Predict System Eigenfrequencies

Low M, single dominant frequency standing wave equations:

$$p' = [A^+ \exp^{jkx} + A^- \exp^{-jkx}] \exp^{-j\omega t}$$

$$u' = [\tfrac{A^+}{\rho c} \exp jkx - \tfrac{A^-}{\rho c} \exp^{-jkx}] \exp^{-j\omega t}$$

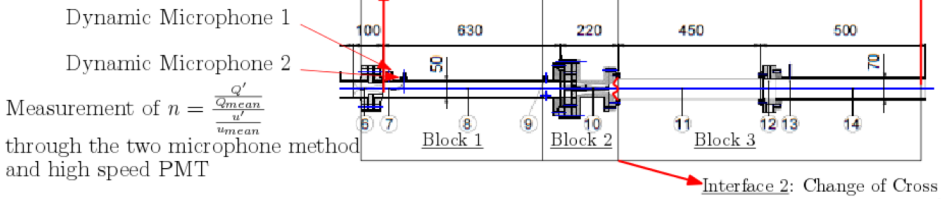
Interface 1: Change of Cross Section

$$p'_{Left} = p'_{Right}$$

$$S_{Left} u'_{Left} = S_{Right} u'_{Right}$$

Boundary Condition u'=0

Boundary Condition p'=0

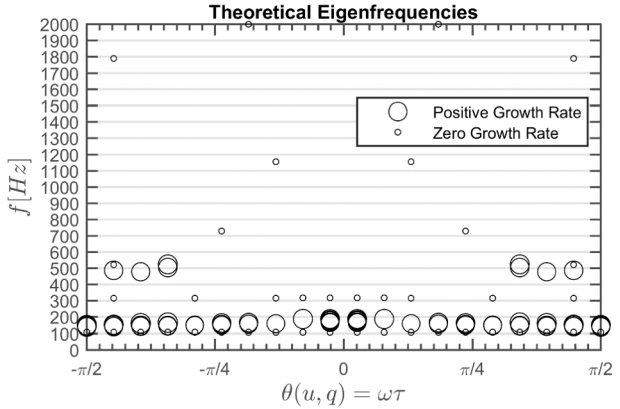


Interface 2: Change of Cross Section
Velocity Jump (Flame)

$$p'_{Left} = p'_{Right}$$

$$u'_{Left} = u'_{Right} \left[\tfrac{S_{Right}}{S_{Left}} + \left(\tfrac{T_{burned}}{T_{unburned}} - 1 \right) n \exp j\omega\tau \right]$$

Model Results: f2 is not predicted as an ustable eigenfrequency of the system



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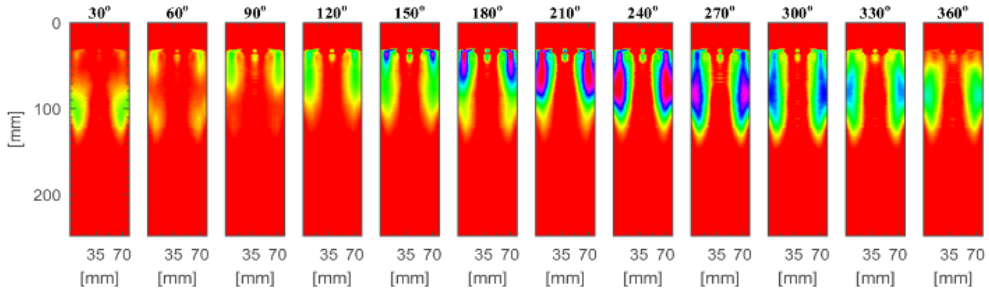
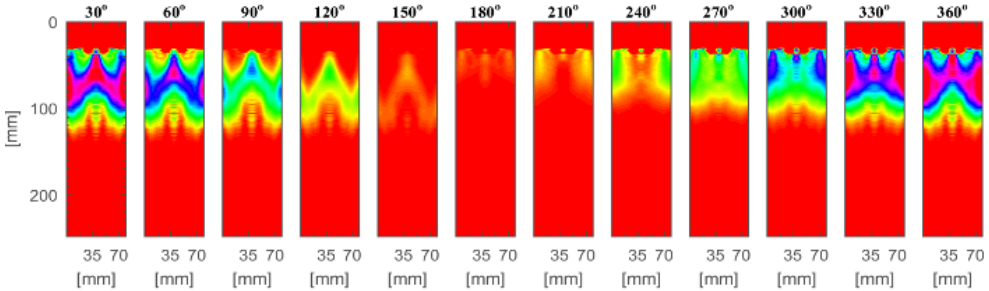
Flame Shape Bifurcation on Increasing Equivalence Ratio-Depiction of Hydrodynamic Structure through DMD

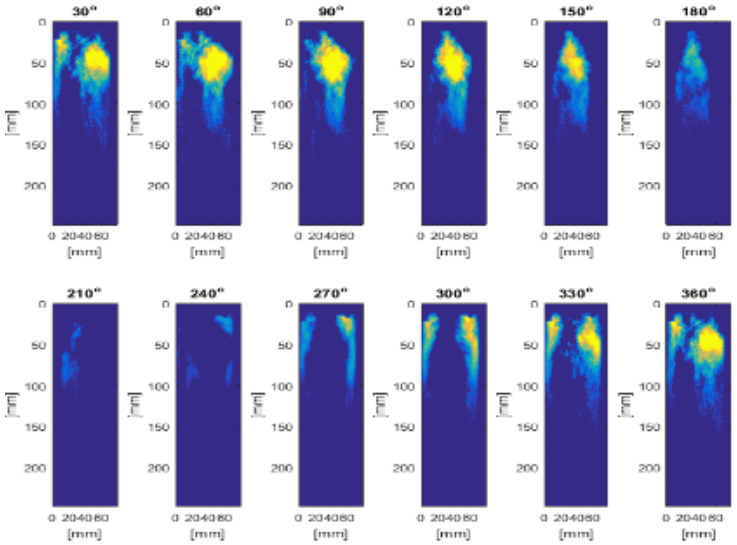
Flame I: CH* distribution for φ=0.55, Re=27000



Flame II: CH* distribution for φ=0.65, Re=27000



Dynamic Mode Decomposition (DMD) of the Subharmonic Frequency



- Abel deconvoluted phase averaged CH* distribution with φ=0.55 and φ=0.65. Correspond to f1=165 Hz for both cases. Time between successive images is 0.5ms.
- Flame I: stabilization on wall shear layers
- Flame II: additional expansion on internal recirculation zone.
- Working hypothesis: flame needs to overcome high strain areas to further anchor on internal recirculation zone shear layers. Then shear layer instability causes the period doubling bifurcation.

- DMD resolves a set of time series into time independent modes.
- Hot combustion products are convected azimuthally around the burner. The frequency associated with it is 82 Hz. The time distance between each frame is 1ms.

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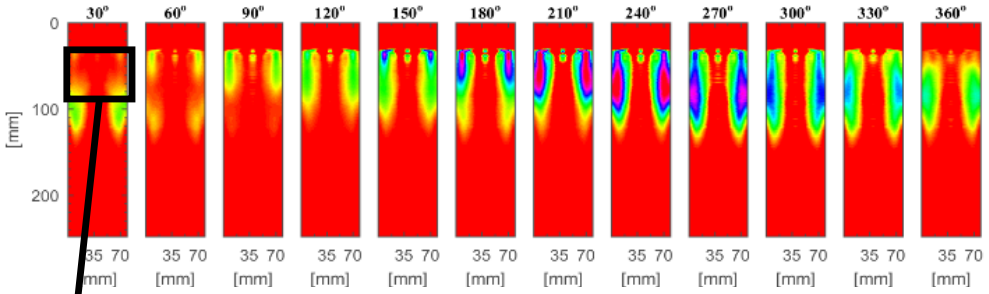
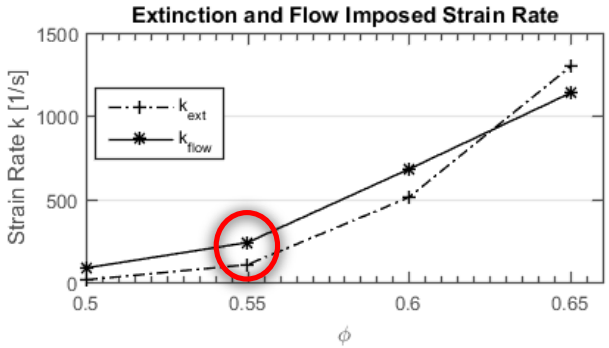
PIV phase averaged flow field on Increasing equivalence ratio

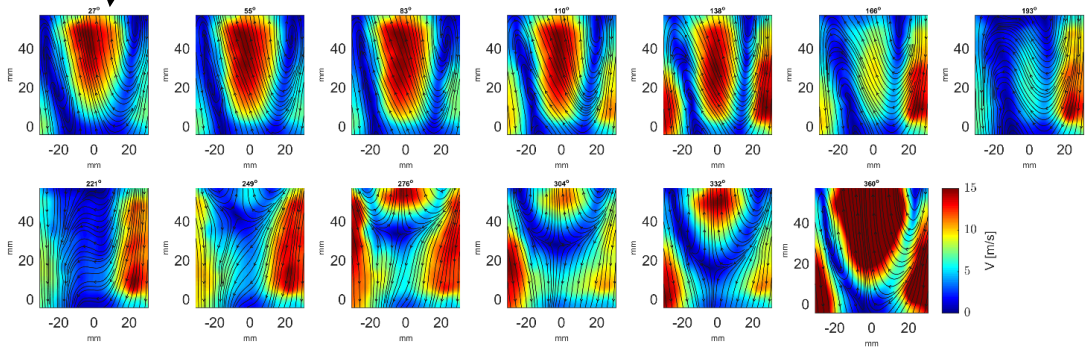
Flame I: CH* distribution for φ=0.55, Re=27000



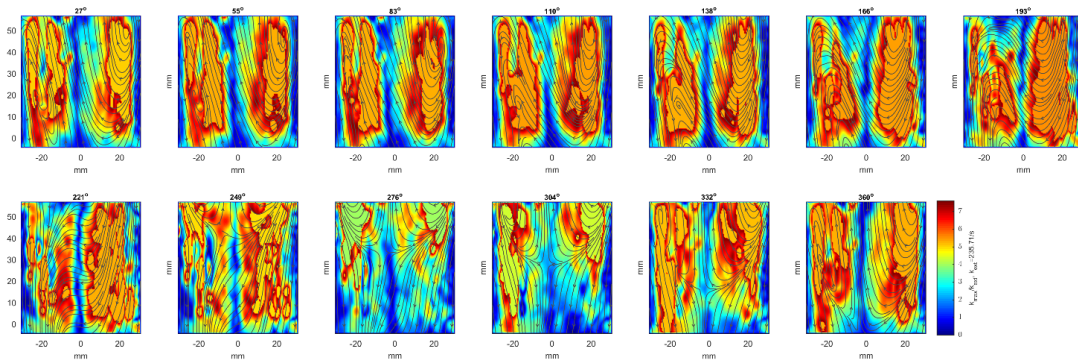


PIV: interrogation area (60 mm x 60 mm, 1024 px x1024 px), 2250 fps

Flame I: Distribution of Velocities for φ=0.55, Re=27000



Flame I: Distribution of Flow Imposed Strain for φ=0.55, Re=27000



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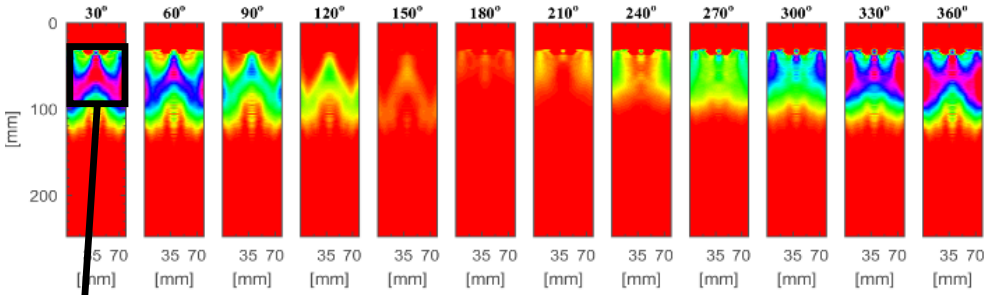
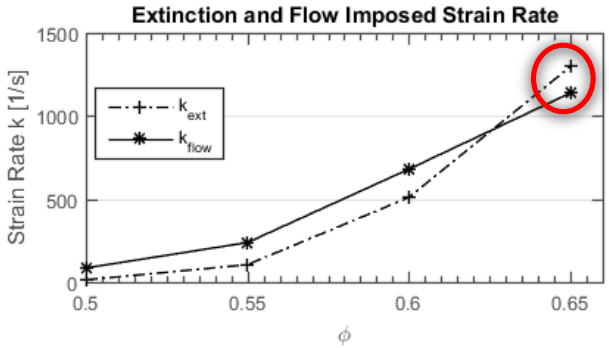
PIV phase averaged flow field on Increasing equivalence ratio

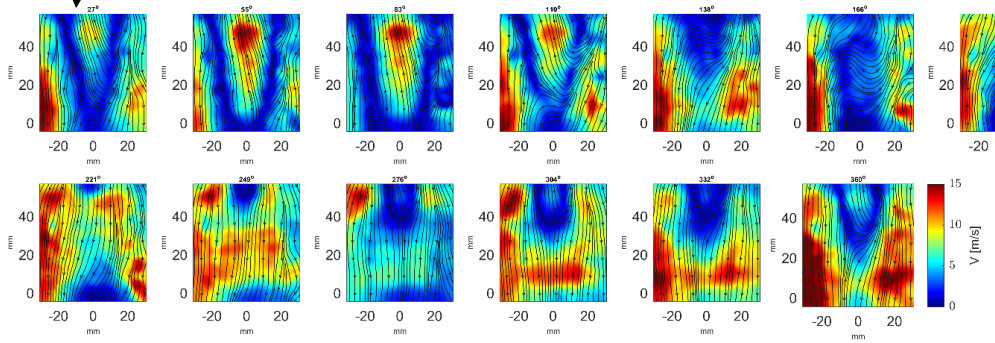
Flame II: CH* distribution for φ=0.65, Re=27000



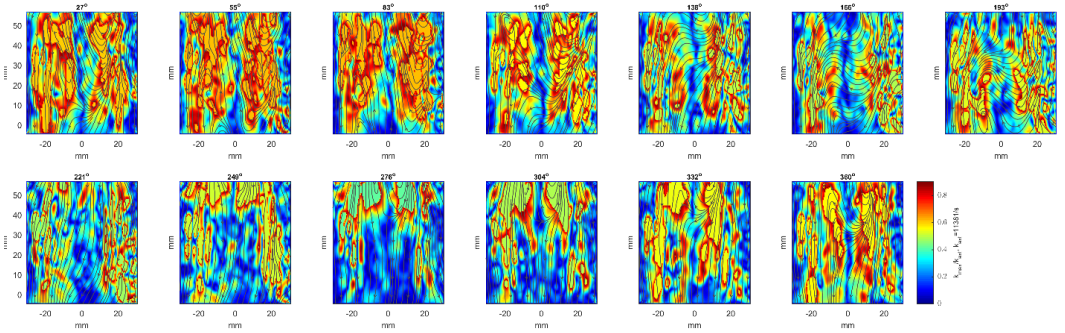


PIV: interrogation area (60 mm x 60 mm1024 px x1024 px), 2250 fps

Flame Ii: Distribution of Velocities for φ=0.65, Re=27000



Flame II: Distribution of Flow Imposed Strain for φ=0.65, Re=27000



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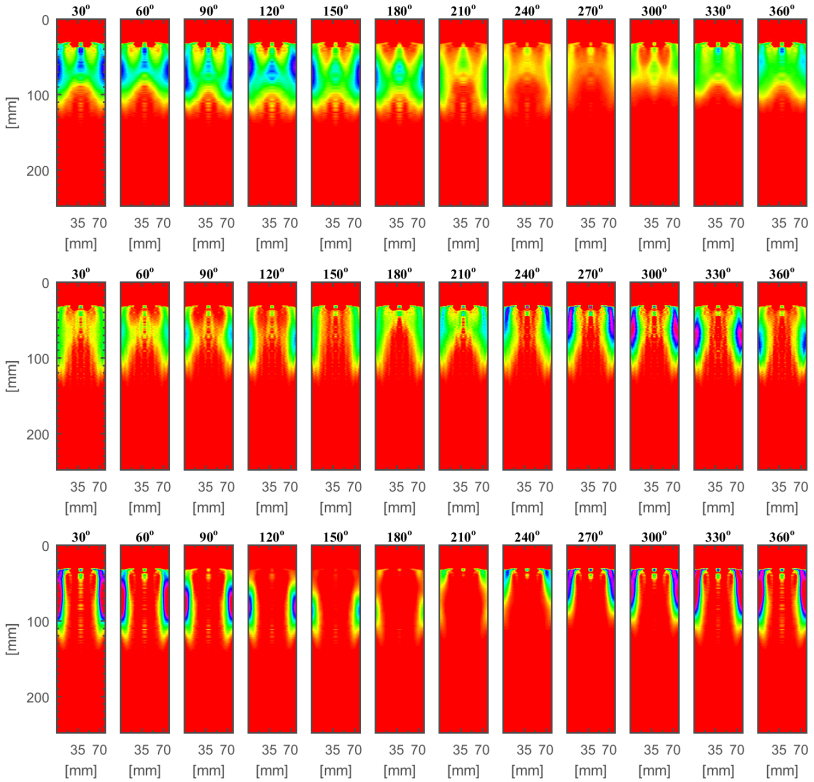
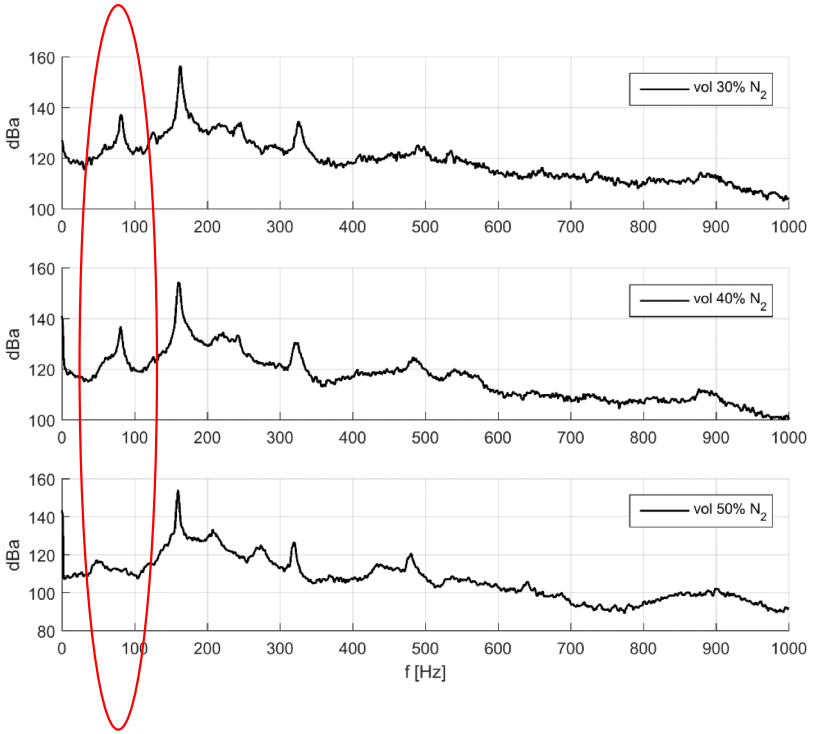
Hypothesis examination on nitrogen diluted propane mixtures: decrease of extinction strain rate on constant equivalence ratio.





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Summary

- We attempt to explain the period doubling bifurcation, the emergence of a hydrodynamic subharmonic frequency and the flame shape bifurcation by scaling the flow imposed strain rate on the flame with the extinction strain rate.
- On increasing the equivalence ratio the flame is able to expand on the internal shear layers of the swirling flowfield since it is able to sustain higher strain rates.
- The working hypothesis is also validated from nitrogen dilution experiments. On increasing nitrogen dilution the flame recedes away from the internal recirculation shear layers.
- Shear layer instabilities might give rise to the period doubling bifurcation.
- DMD decomposition on CH* distribution images acting as a proxy of heat release rate depict a structure convecting hot combustion products azimuthally.

Current Work

- DMD analysis on PIV flow fields to increase the understanding on the coherent structure responsible for the period doubling bifurcation.
- OH PLIF measurements to account for the local curvature contribution in the stretch rate.

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