Bluff Body Flames Near the Global Stability Boundary

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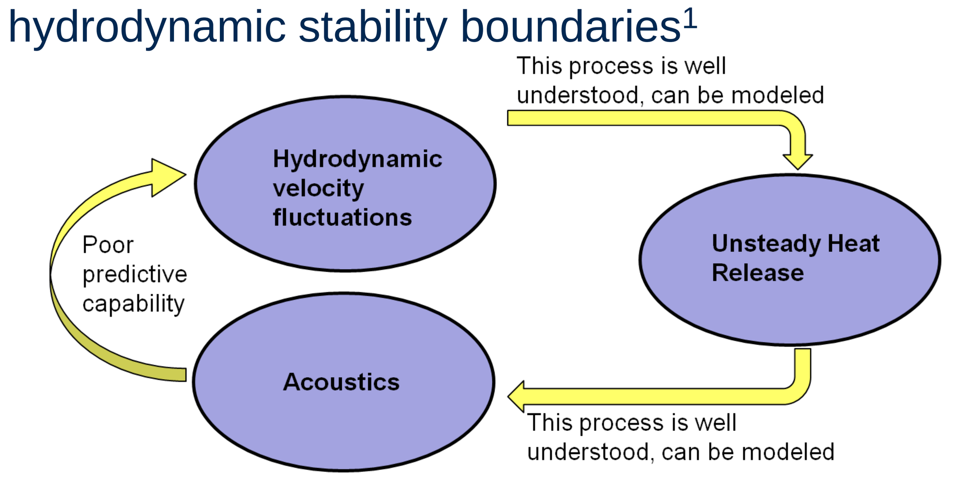
Introduction

Motivation

Combustion instabilities are a leading cause of combustor problems such as damage, blowout, and down-time

- Combustion instabilities are poorly understood, particularly when coupled with hydrodynamic stability boundaries[1]



- Bluff body wake is a simple, canonical flow field, well suited for fundamental combustion instability studies

Bluff Body Flow Dynamics

Unforced bluff body flow fields exhibit Von Karman vortex street[2]

- Vortex street is the flow's natural dynamics- it is a **global instability**
- Consists of alternating vortex shedding at global mode frequency

Reacting Flow Dynamics

Combustion may suppress the vortex street[3]

- **High density** ratio flames suppress vortex street- flow is **globally stable**
- **Low density** ratio flames permit vortex street- flow is **globally unstable**

Forced Flow Dynamics

- If the flow is globally stable[4]
  - Flow responds to acoustic forcing
  - Longitudinal forcing causes symmetric vortex shedding
- If the flow is globally unstable[5]
  - Flow resists longitudinal forcing
  - Flow may respond at forcing frequency if forcing frequency is close to global mode frequency

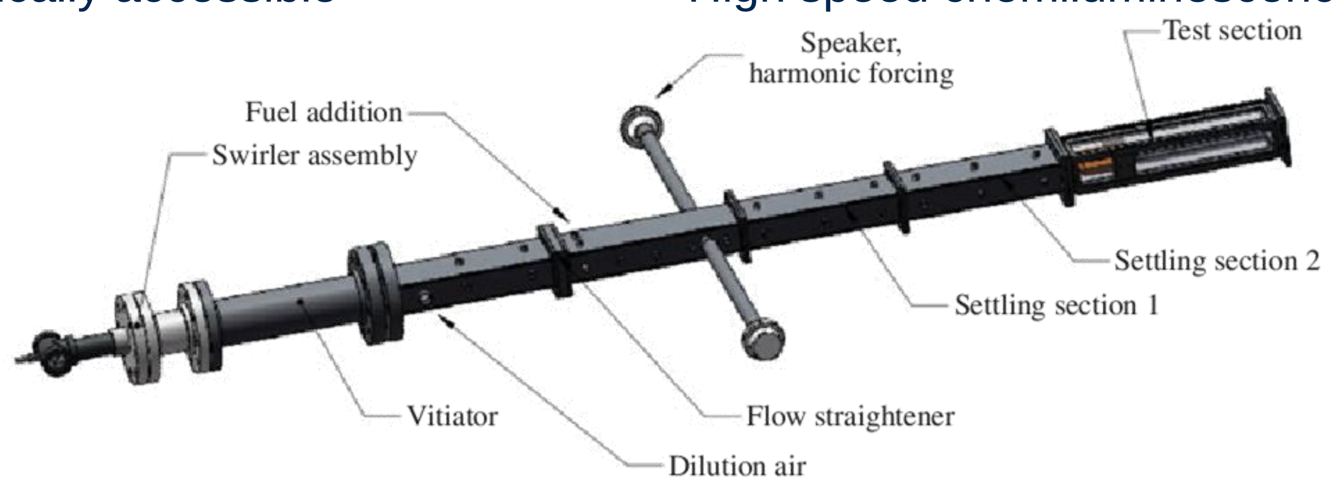
Experimental Methods

Combustor

- Vitiated bluff body combustor
- Optically accessible

Diagnostics

- Particle image velocimetry
- High speed chemiluminescence



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Objectives

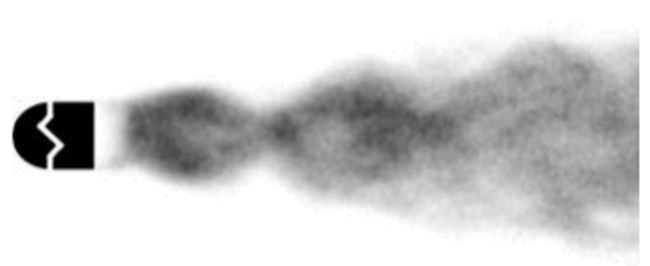
What: Experimentally characterize forced response of reacting bluff body wakes

How: Systematically sweep forcing frequency relative to global mode frequency with density ratio near stability limit

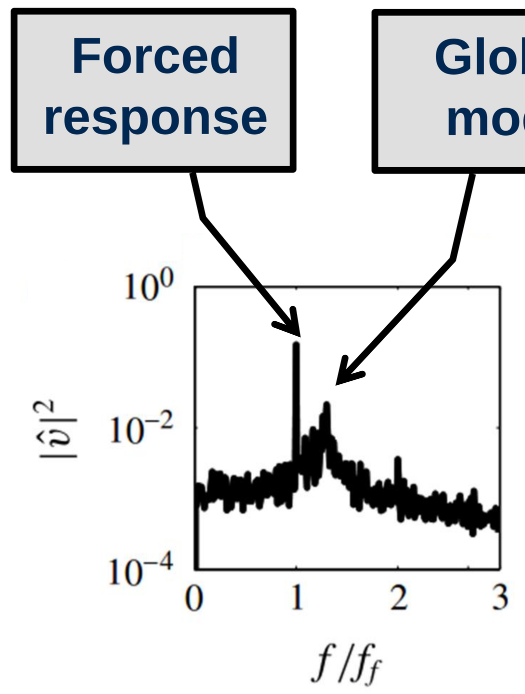
Results

Off-resonance

- Forcing frequency far from global mode frequency
- Flame images show symmetric forced response (varicose)



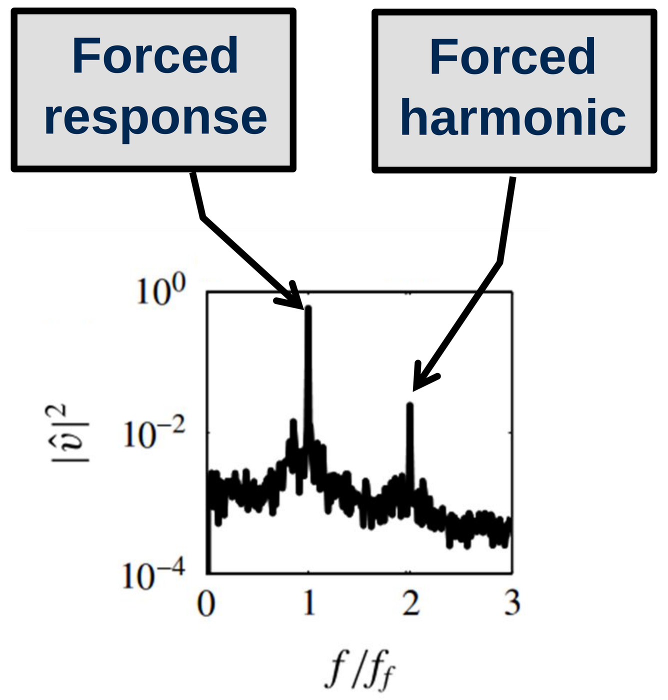
- Velocity spectra show responses
  - At forcing frequency
  - At global mode frequency



Resonant Amplification

- Forcing frequency close to global mode frequency
- Flame images show asymmetric forced response (sinuous)

- Velocity spectra show
  - Very strong response at forcing frequency
  - First harmonic of forcing



Observations

1. Forcing far from global mode frequency causes symmetric forced response
2. Forcing close to global mode frequency causes asymmetric forced response
3. Density ratio has little influence, as long as its near the stability boundary- unlike unforced flows where density ratio is sensitive!

Analysis

Sinuous/varicose mode decomposition

Decompose the flow as sum of sinuous and varicose modes

- Global mode shape is sinuous
- Forcing excites varicose structure

$$\left.\begin{aligned} u(x,y,t) &= u_s(x,y,t) + u_v(x,y,t) \\ v(x,y,t) &= v_s(x,y,t) + v_v(x,y,t), \end{aligned}\right\}$$

Sinuous/Varicose modes defined by top/bottom symmetry:

$$\text{Sinuous mode: } u_s(x,y,t) = \frac{u(x,y,t) - u(x,-y,t)}{2};$$

$$v_s(x,y,t) = \frac{v(x,y,t) + v(x,-y,t)}{2}$$

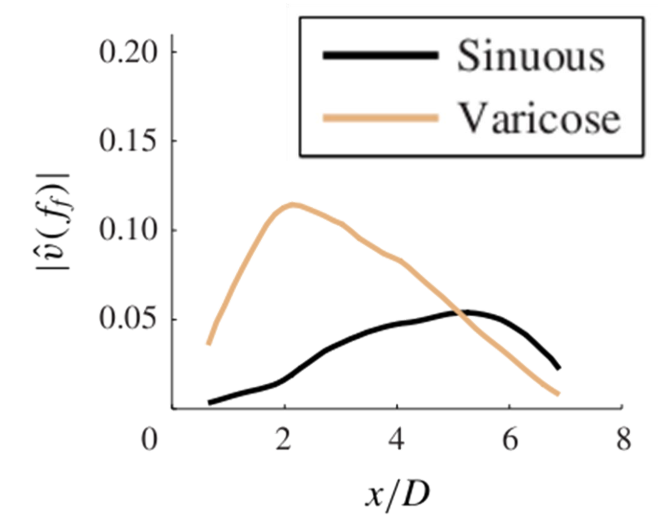
$$\text{Varicose mode: } u_v(x,y,t) = \frac{u(x,y,t) + u(x,-y,t)}{2};$$

$$v_v(x,y,t) = \frac{v(x,y,t) - v(x,-y,t)}{2}.$$

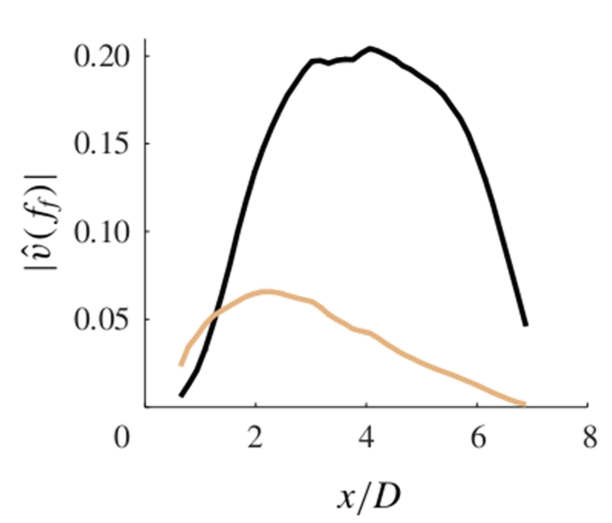
Axial dependence of sinuous and varicose modes

- Sinuous mode grows rapidly to dominate resonant response
- Varicose mode dominates off-resonant response

Off Resonance



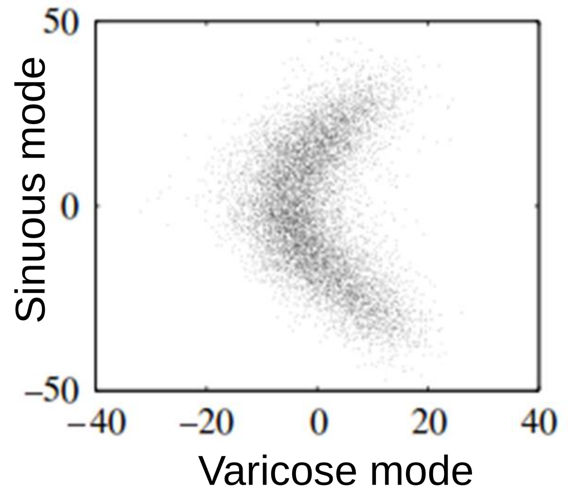
Resonant Amplification



Coupling mechanisms

In resonance, sinuous mode couples to varicose mode through first Harmonic of varicose mode

- Presence of first harmonic evident in Spectra
- Phase coupling of varicose harmonic is evident in phase portraits of sinuous motion vs varicose motion



Conclusions

1. Resonance occurs forcing frequency and global frequency are close
2. Off-resonant forced response is symmetric
3. Resonant forced response is asymmetric, which tends to reduce heat release response

References

(1) Lieuwen, Tim C. *Unsteady combustor physics*. Cambridge University Press, 2012.

(2) Perry, A. E., M. S. Chong, and T. T. Lim. "The vortex-shedding process behind two-dimensional bluff bodies." *Journal of Fluid Mechanics* 116 (1982): 77-90.

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(5) Bishop, R. E. D., and A. Y. Hassan. "The lift and drag forces on a circular cylinder oscillating in a flowing fluid." In *Proceedings of the Royal Society of London A: Mathematical, Physical and Engineering Sciences*, vol. 277, no. 1368, pp. 51-75. The Royal Society, 1964.