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Simulating thermoacoustic response of multiple burners in gas turbine combustors

Dong Yang, Davide Laera, Yu Xia, Aimee S. Morgans

Department of Mechanical Engineering
Imperial College London

Email: d.yang13@imperial.ac.uk

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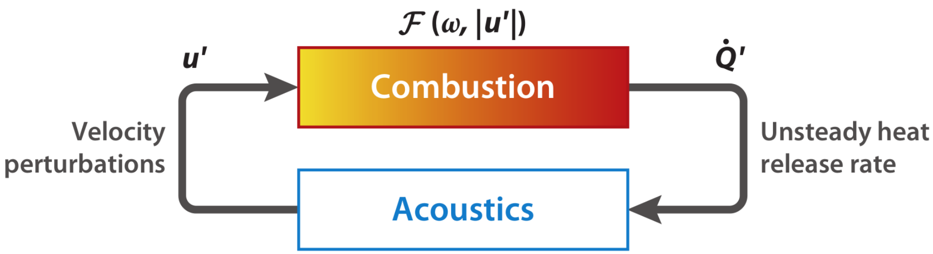
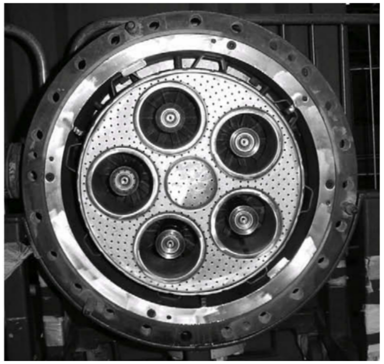
Content

- Introduction
- Objectives
- Simulation of single burner
- Simulation of multiple burners
- Conclusions and future works

What is thermoacoustic instability?



Thermoacoustic oscillations
[Candel et al. 2014]



New burners

Damaged burners
[Goy et al. 2005]

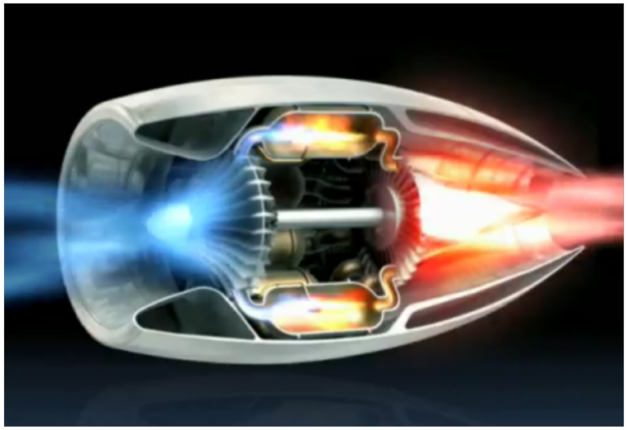
Commonly encountered in
- aero engine,
- land-based gas turbine,
- rocket engine

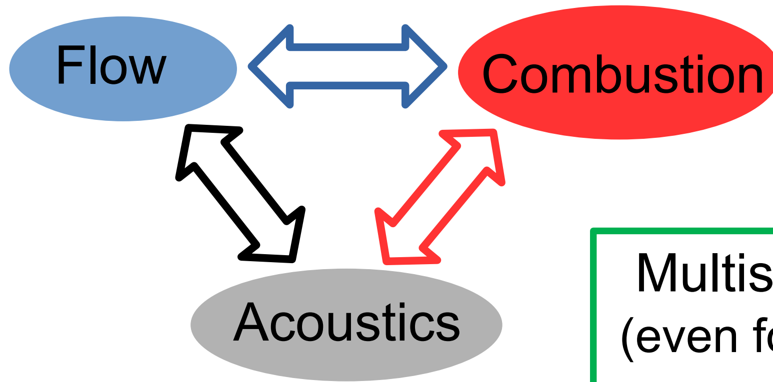
combustors

Damaged
turbine blades

- *S.Candel, D.Durox, T. Schuller, J-F. Bourgouin and J.P.Moeck, In: Annu. Rev. Fluid Mech., 2014.*
- *C.J.Goy, S.R.James and S.Rea, In: Prog. Astronaut. Aeronaut., 2005.*

Why is prediction challenging?



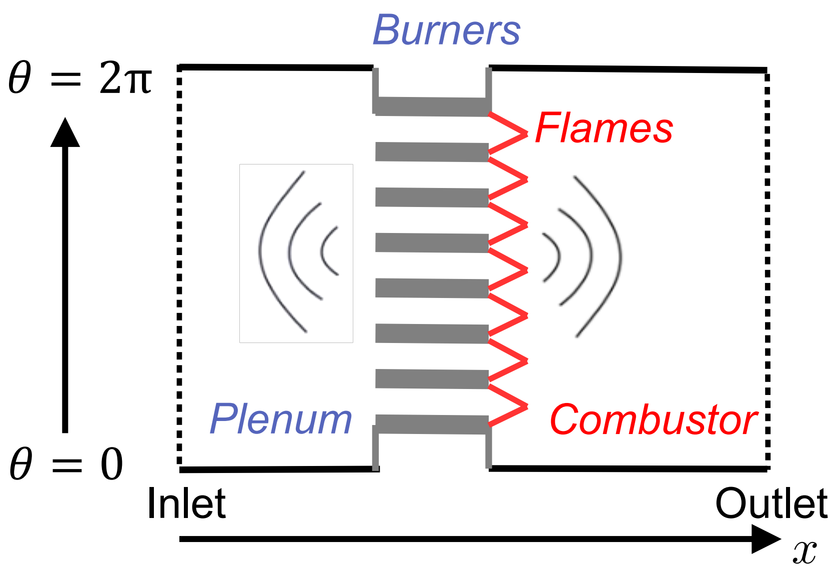


Multiscale coupling (even for single-burner combustors)

+

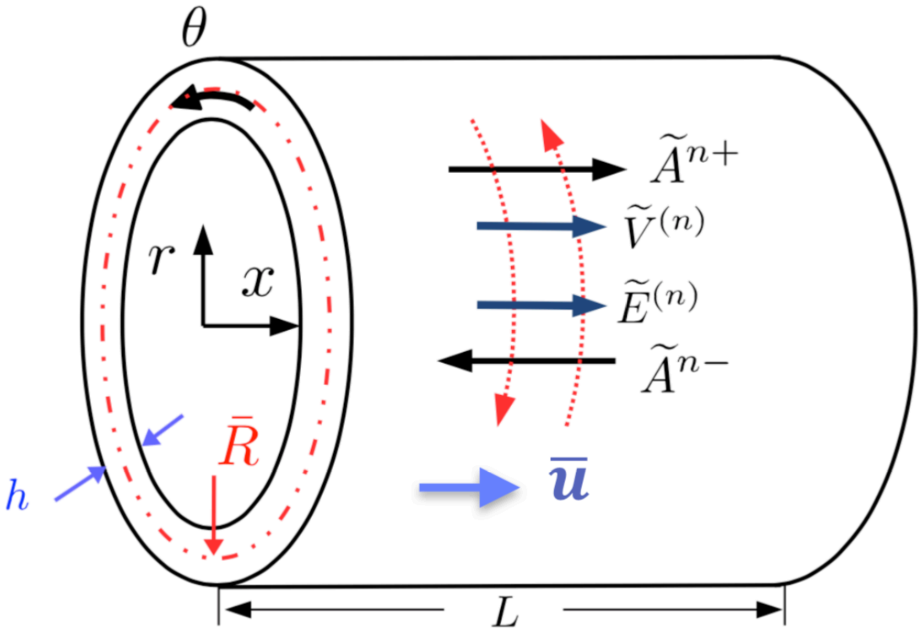
Multiple burners

Full CFD and full-scale experiments are too expensive!



2-D schematic view of a real (can-) annular combustor

Low-order network model – linear perturbations



Constant cross sectional area

+

Uniform mean flow

+

Linear perturbations

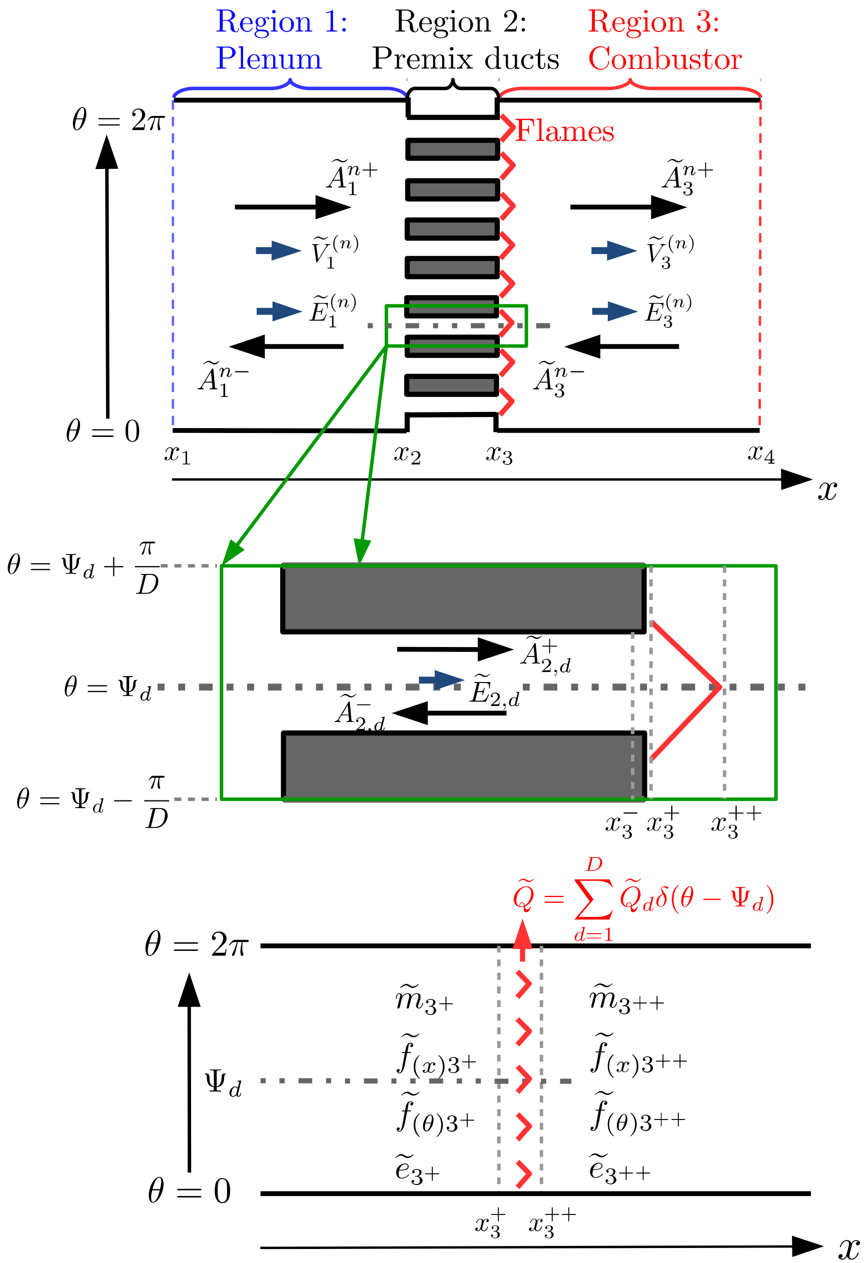
Analytical solution can be obtained by using modal expansion.

Acoustics: $$\left(\frac{1}{\bar{c}^2}\frac{\bar{D}^2}{Dt^2} - \nabla^2\right)p' = 0,$$

Entropy: $$\bar{\rho}\bar{T}\frac{\bar{D}s'}{Dt} = 0,$$

Vorticity: $$\frac{\bar{D}\boldsymbol{\xi}'}{Dt} = \mathbf{0},$$

$$(\bar{D}/Dt = \partial/\partial t + \bar{\boldsymbol{u}} \cdot \nabla)$$

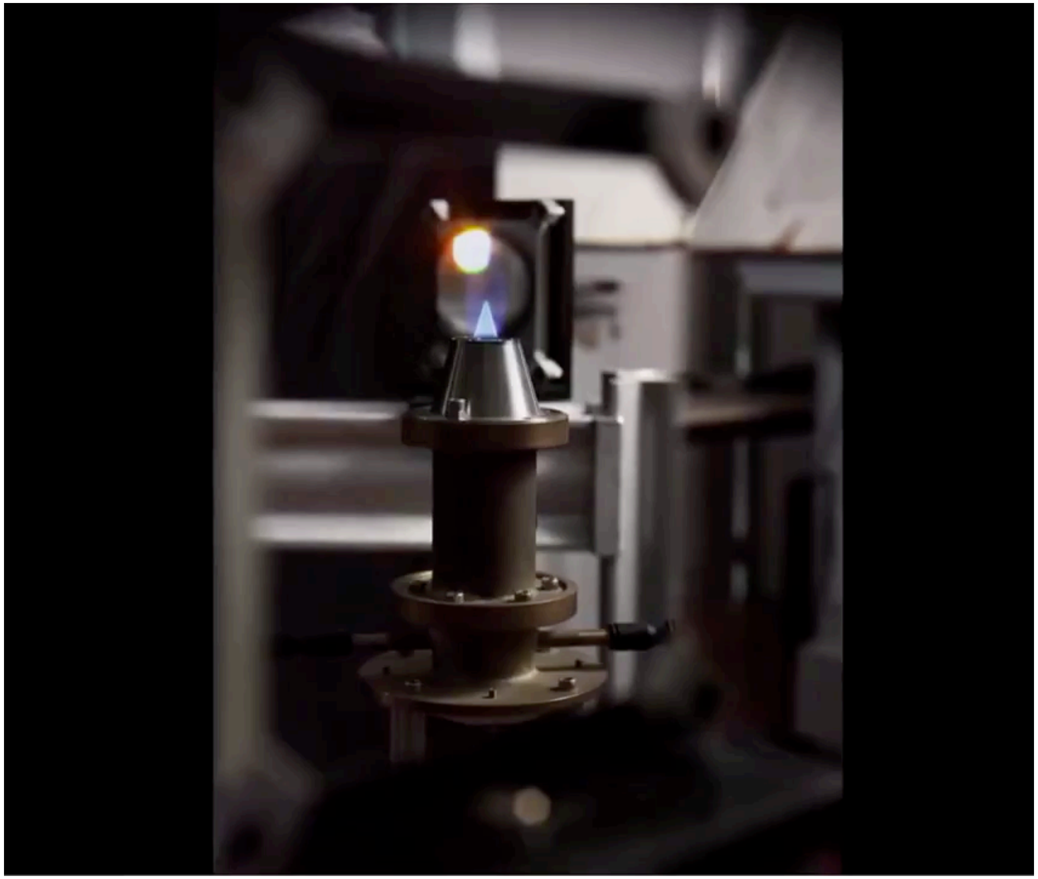


Low-order network model for annular combustors

- For each section
  -- Modal expansion solution
- Flow contraction/expansion
  -- Isentropic/momentum balance
- Across flames
  -- Flame model: $\dfrac{\widetilde{Q}_d}{\bar{Q}_d} = \mathcal{T}^{(d)}(\omega, |\widetilde{u}_d|)\dfrac{\widetilde{u}_d}{\bar{u}_d}$
- Inlet/outlet
  -- Acoustic boundary conditions

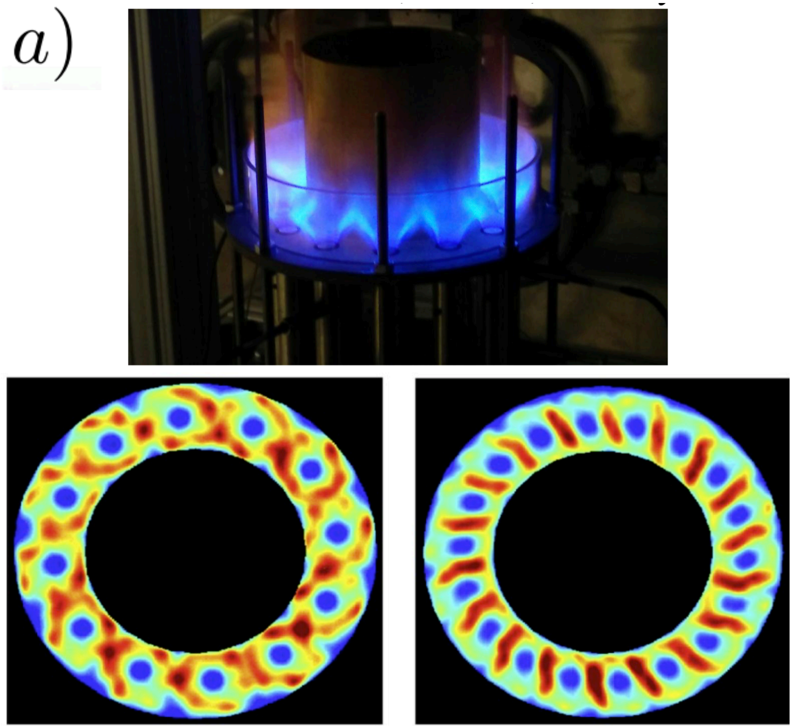
The model has been proved being able to capture very different thermoacoustic mode patterns in annular combustors, e.g. **longitudinal, spinning, standing** and **slanted** modes.
Yang et al. J. Sound Vib. 2019

Flame under acoustic perturbation

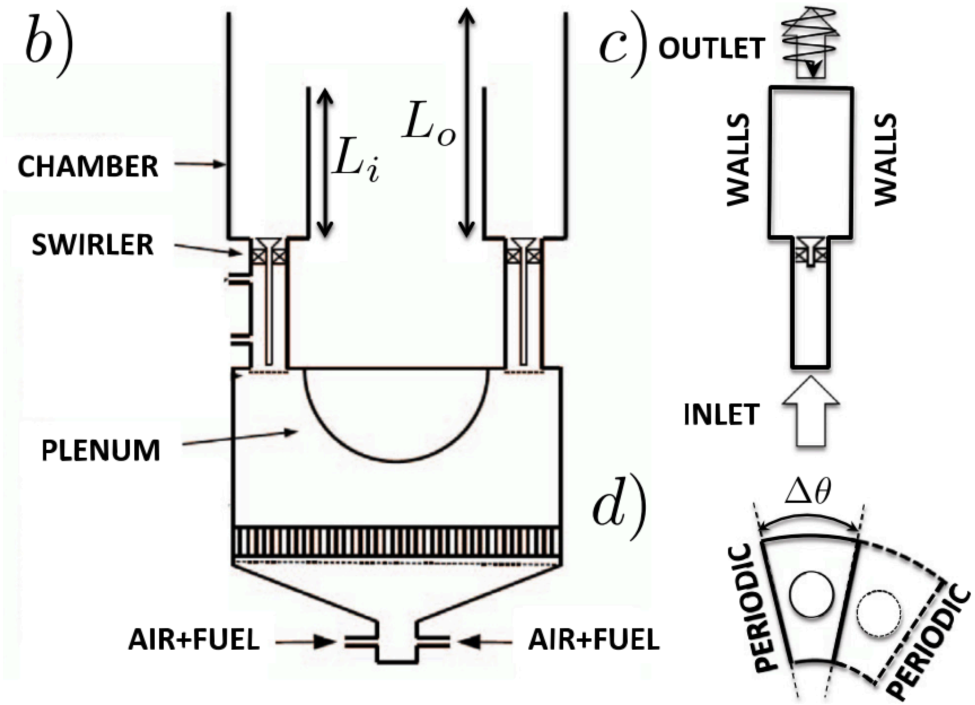


Movie by Daniel Durox, EM2C Lab, Centrale Supelec, Paris

Experiment rig from Norwegian University of Science and Technology (NTNU)



Worth and Dawson, Proceeding of Combustion Institute (2013)



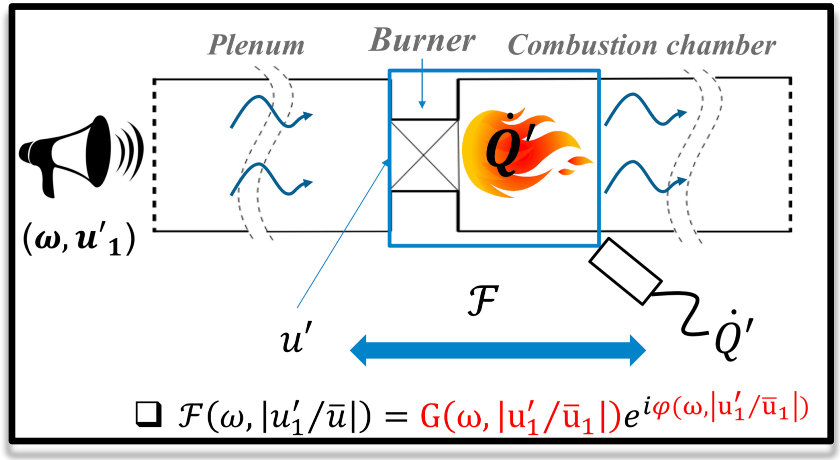
Bauerheim et al., Proceedings of Combustion Institute (2015)

- Different number of burners (with different burner-burner distances) are used.
- Circumferentially spinning, standing, and mixed mode patterns are observed.

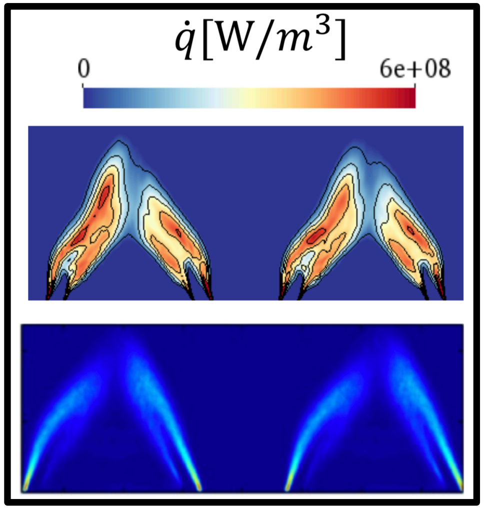
Objectives

We aim at

- using LES to numerically predict flame unsteady heat release response to acoustic perturbations

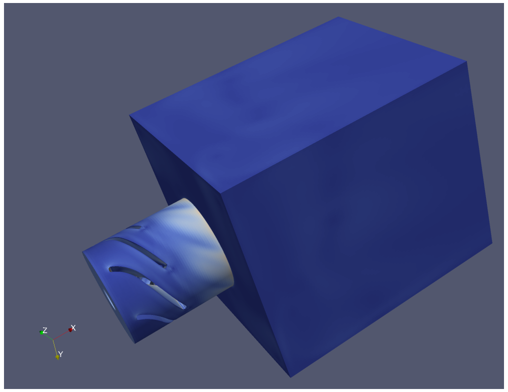


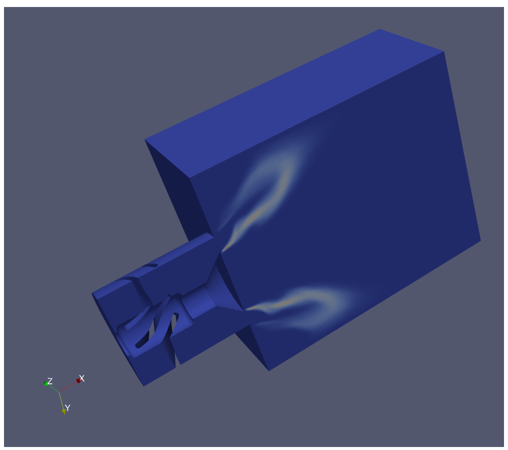
- studying the effects of flame-to-flame interactions on flame acoustic response

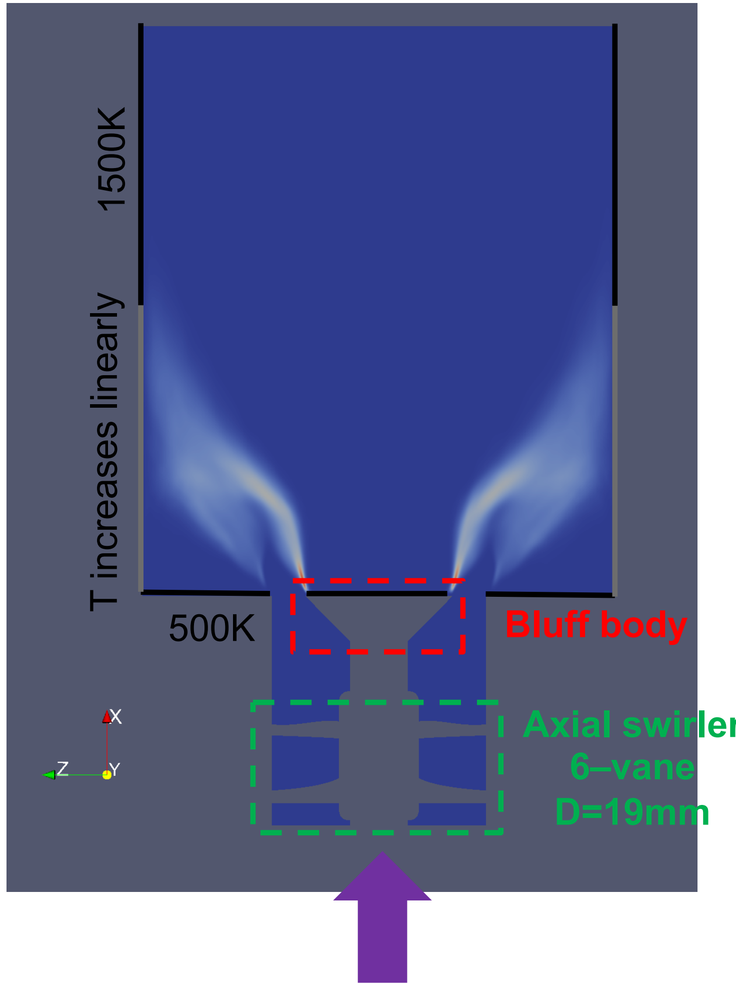


- incorporating the flame response into low-order network models to study its effect on thermoacoustic instabilities in annular combustors

Single burner case



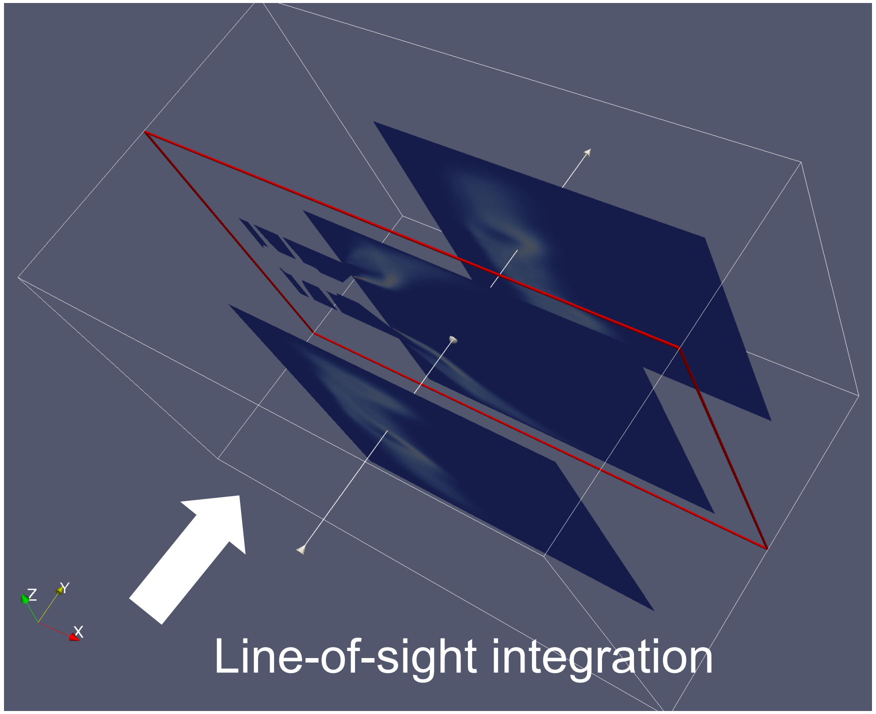




C_2H_4/air premixed, ϕ=0.7
T=300K, U=10m/s, Re~15,000

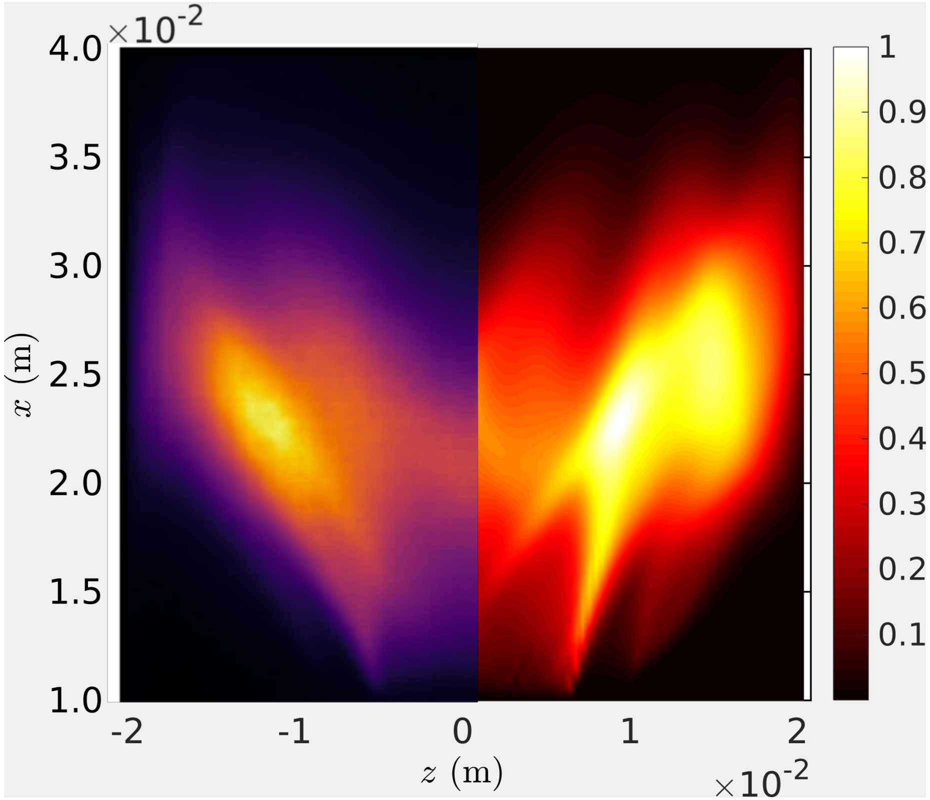
- Incompressible OpenFOAM LES
- 2-step C_2H_4/air reaction mechanism
- Combustion model: Partially-Stirred Reactor (PaSR)
- SGS turbulence model: Constant Smagorinsky
- ~9M mesh cells
- Adiabatic, or wall temperature -- *based on experimental observations*

Single burner case – mean flame shape



81 cutting planes in the y direction are used to ensure integration convergency

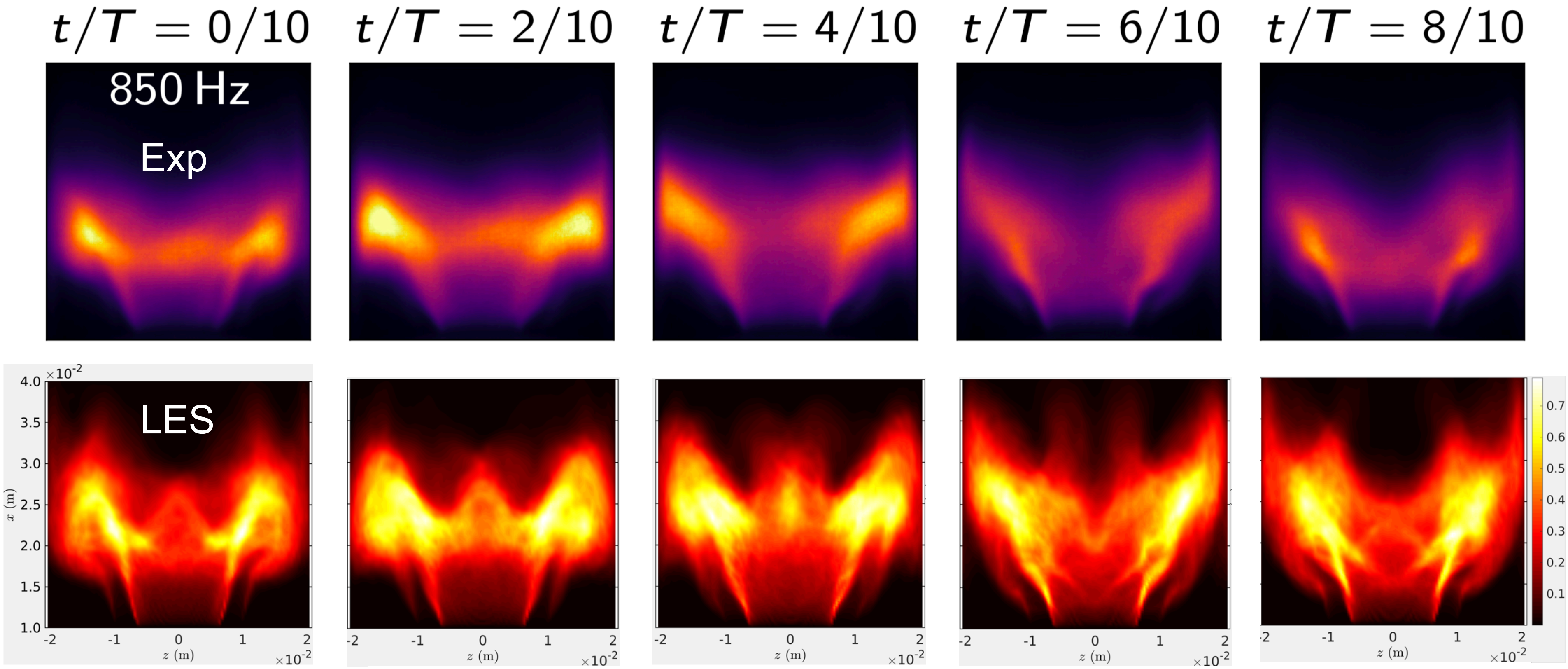
Exp LES



Mean flame shape

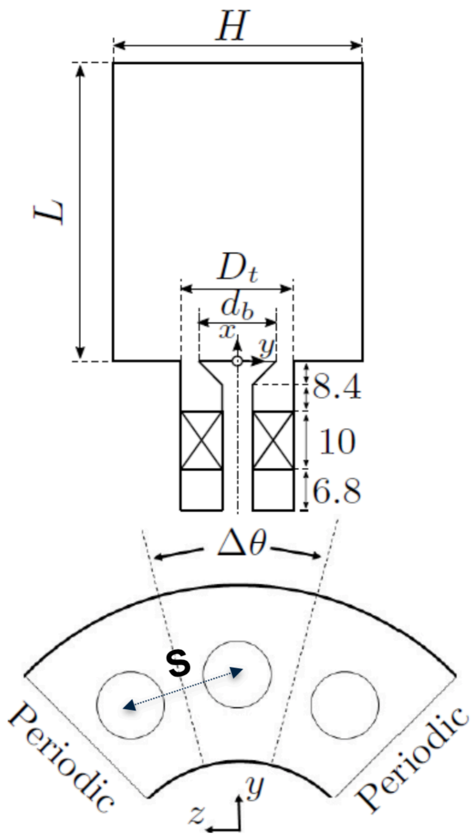
Single burner case – 10% inlet velocity perturbation

$$f = 850\text{Hz},\ T = 1/f,\ u_{in} = \bar{u} \times [1 + 0.1 \times \sin(2\pi f(t - t_0))]$$



Phase-averaged flame dynamics. (Top) Experiment and (bottom) numerical results -- 60 cycles are used in the numerical results. Further validation is still ongoing.

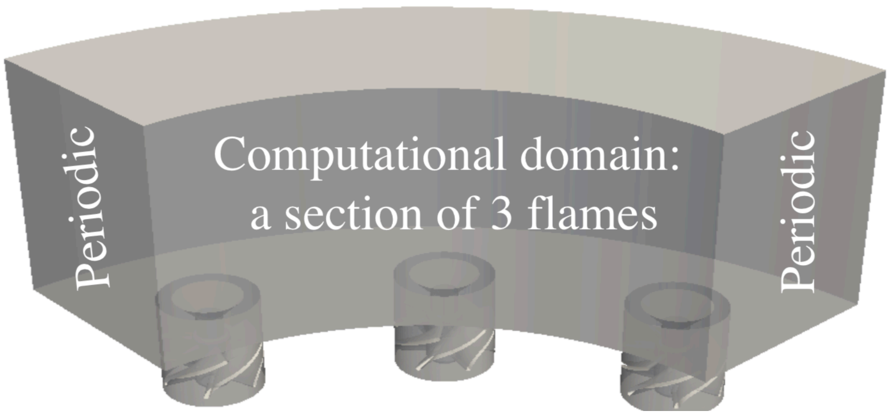
Three-burners case – presented by Yu Xia UKCTRF2018



Two flame distances (S) are considered

1. **S = 2.33 D, Δθ = 30°** (flames separated)
2. **S = 1.56 D, Δθ = 20°** (flames closer)

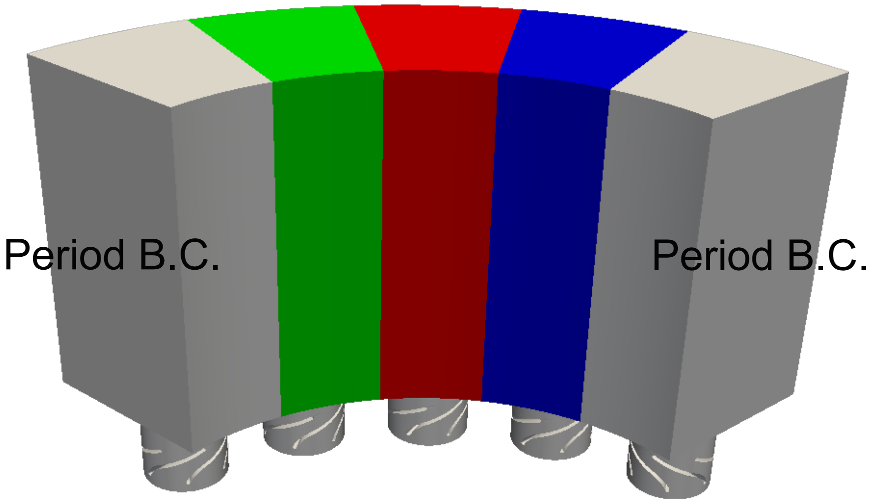
- Incompressible OpenFOAM-LES ($(\partial\rho/\partial p)_T = 0$)
  - Adiabatic side walls
  - 2-step C_2H_4/air reaction scheme
  - ~26M mesh cells for **1** and ~24M cells for **2**



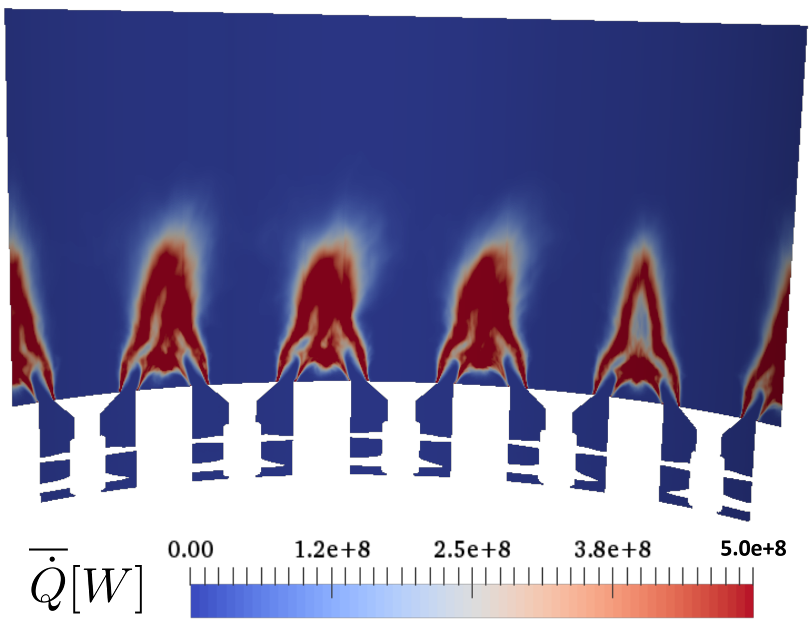
Main conclusions:

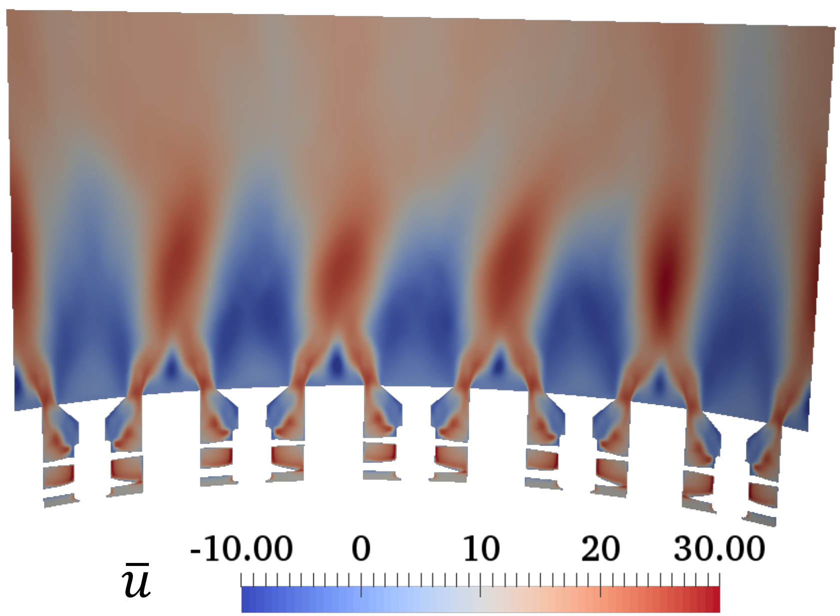
- An isolated single flame cannot represent the flame response in an annular combustor.
- Different flame separation distances lead to different flame response gains and phases.

Five-burners case



- Distance between two flames S=1.56D
- Perfectly premixed ethylene-air ($\phi = 0.85$)
- WALE SGS turbulence model
- $T_{wall} = 1000K$



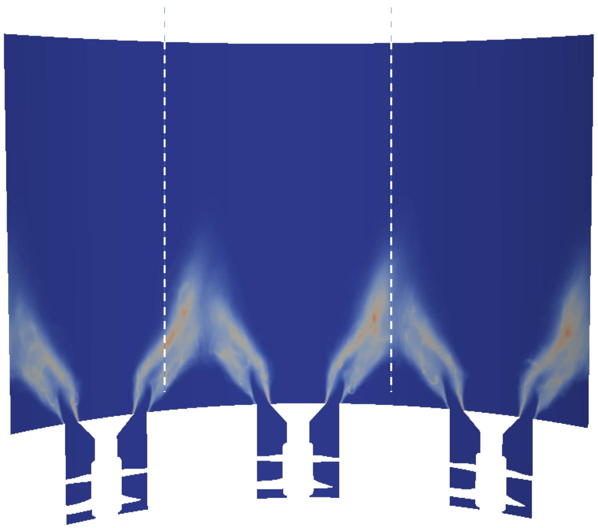


Matrix of flame response

Definition of FTF: $\frac{Q'}{Q} = FTF\frac{u'}{u} = G exp(i\emptyset)\frac{u'}{u}$ G: gain $\emptyset$: phase

- Flames 1-3 are now forced (together and separately) – 5 flames with periodic boundary condition at the two sides are used to avoid interaction between 1 and 3.

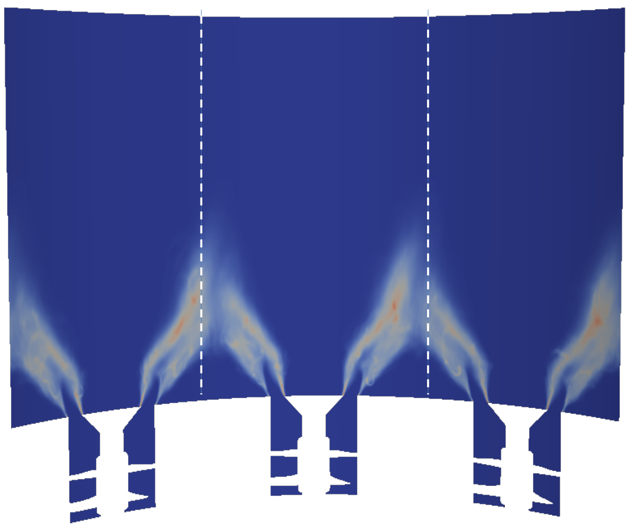
- For multiple flames in an annular combustor, the response of one flame is also affected by neighboring flames: Gij and Øij: i -- flame no., j -- forcing no.



$$\begin{bmatrix} \frac{Q1'}{Q1} \\ \frac{Q2'}{Q2} \\ \frac{Q3'}{Q3} \end{bmatrix} = \begin{bmatrix} G11\exp(\emptyset 11) & G12\exp(\emptyset 12) & G13\exp(\emptyset 13) \\ G21\exp(\emptyset 21) & G22\exp(\emptyset 22) & G23\exp(\emptyset 23) \\ G31\exp(\emptyset 31) & G32\exp(\emptyset 32) & G33\exp(\emptyset 33) \end{bmatrix} \begin{bmatrix} \frac{u1'}{u1} \\ \frac{u2'}{u2} \\ \frac{u3'}{u3} \end{bmatrix}$$

Linear superposition at low forcing amplitudes

E.g. Heat release response of flame 1



Case 1 forcing all 3 flames with the same velocity amplitude:

$$\frac{Q1'}{Q1} = G1exp(i\emptyset 1)\frac{u'}{u}$$

Q: Are the two cases equivalent?

Case 2 forcing each flame one by one:

$$\frac{Q1'}{Q1} = [G11exp(i\emptyset 11) + G12exp(i\emptyset 12) + G13exp(i\emptyset 13)]\begin{bmatrix} \frac{u'}{u} \\ \frac{u'}{u} \\ \frac{u'}{u} \end{bmatrix}$$

Linear superposition at low forcing amplitudes

Forcing at 500Hz and **10%** of the burner inlet velocity amplitude

Response of **Flame 1**

Case 1 (forcing all together): $G1 = 2.05,\ \emptyset 1 = 3.20\ \text{rad}$

Case 2 (forcing separately and sum): $G1 = 2.11,\ \emptyset 1 = 3.12\ \text{rad}$

Response of **Flame 2**

Case 1 (forcing all together): $G2 = 1.81,\ \emptyset 2 = 3.16\ \text{rad}$

Case 2 (forcing separately and sum): $G2 = 1.98,\ \emptyset 2 = 3.15\ \text{rad}$

Response of **Flame 3**

Case 1 (forcing all together): $G3 = 1.86,\ \emptyset 3 = 3.19\ \text{rad}$

Case 2 (forcing separately and sum): $G3 = 1.96,\ \emptyset 3 = 3.29\ \text{rad}$

- Linear superposition is approximately valid at 500Hz and 10% forcing amplitude for the present case.
- Flame response at different frequencies and forcing amplitude needs further study.

Conclusions and future works

Conclusions

- Incompressible LES and simple chemistry are used to study both mean and dynamic behaviors of a single premixed swirling flame.
- The effect of flame-to-flame interaction in annular combustors on flame response is studied in the linear regime - linear superposition is confirmed.

Future works

- Study more frequencies and nonlinear effect at higher forcing levels
- Incorporate FTF/FDF into low-order network models to study their effect on thermoacoustic instabilities in annular combustors

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Large eddy simulation of acoustic-hydrodynamic interaction for a bluff body burner

Jialin Su, Dong Yang, Aimee S. Morgans

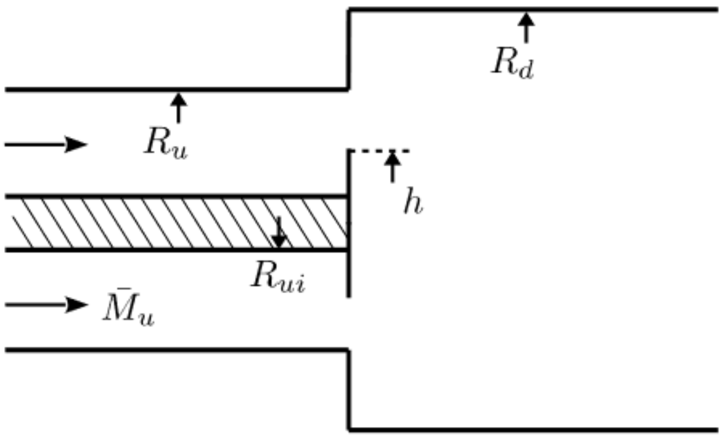
Department of Mechanical Engineering

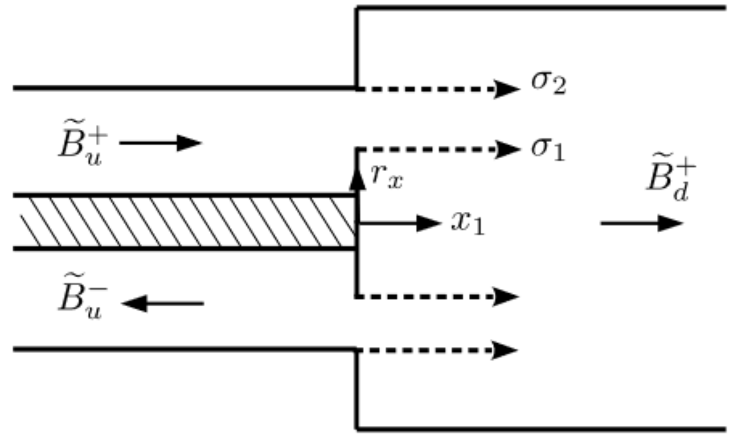
Email: jialin.su@imperial.ac.uk

Content

- Background and objectives
- Preliminary results

Theoretical model





stagnation enthalpy: $B = C_p T + |\boldsymbol{u}|^2/2$

vorticity

$$\nabla B = \nabla p/\rho + \nabla(|\boldsymbol{u}|^2)/2$$

$$\frac{\partial \boldsymbol{u}}{\partial t} + (\boldsymbol{u}\cdot\nabla)\boldsymbol{u} + \nabla p/\rho = \boldsymbol{0}$$

$$(\boldsymbol{u}\cdot\nabla)\boldsymbol{u} \equiv \nabla(|\boldsymbol{u}|^2)/2 + \boldsymbol{\omega}\times\boldsymbol{u}$$

Momentum: $\dfrac{\partial \boldsymbol{u}}{\partial t} + \nabla B = -(\boldsymbol{\omega}\times\boldsymbol{u})$

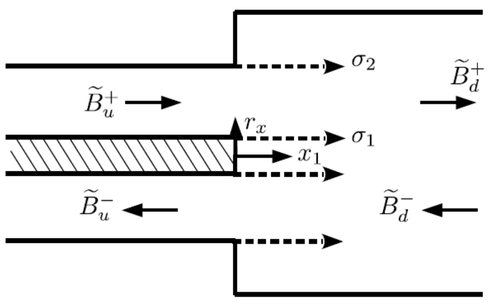
Isentropic, no viscosity and volume forces

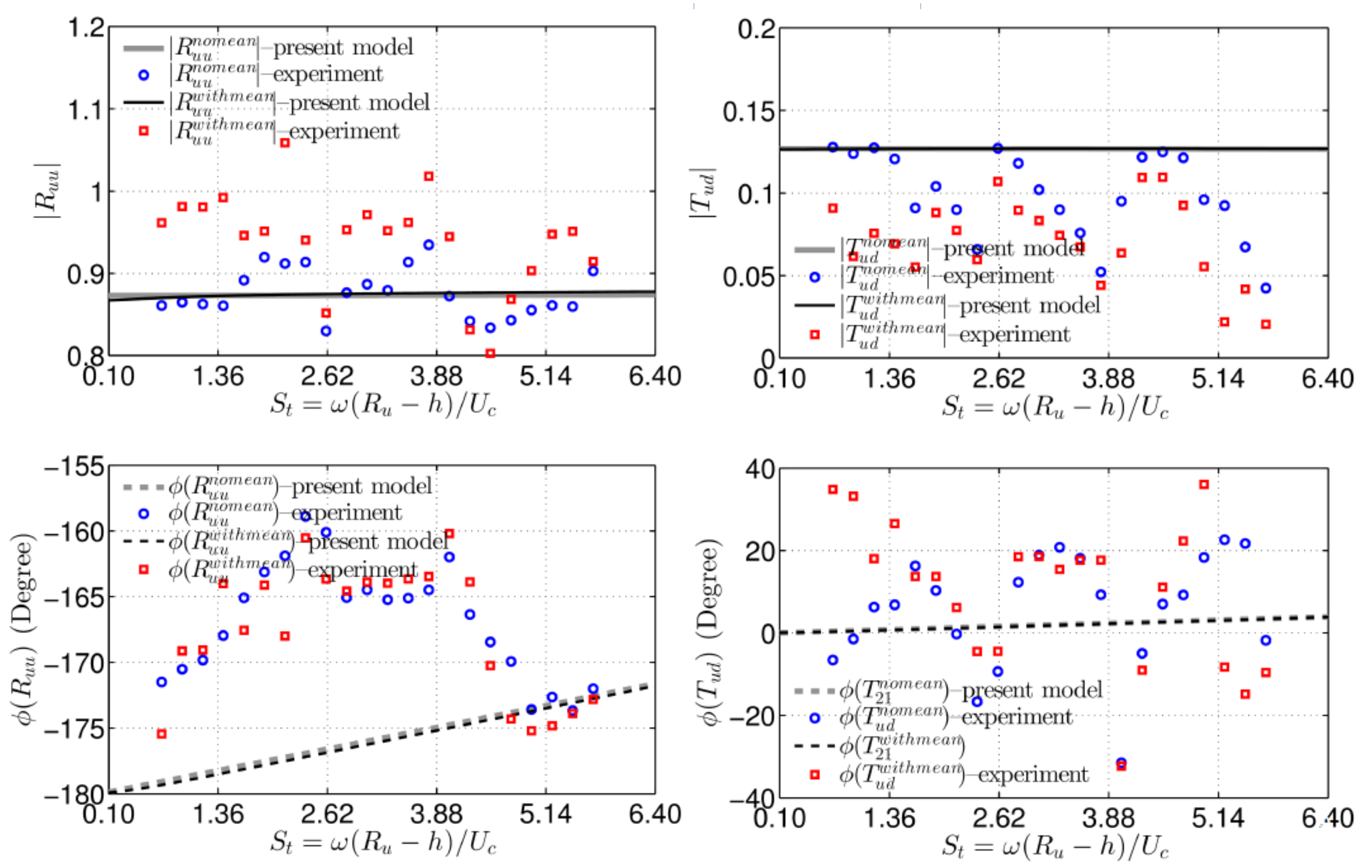
Mass: $\dfrac{\partial \rho}{\partial t} + \nabla\cdot(\rho\boldsymbol{u}) = 0$

$$\Rightarrow \left(\frac{1}{\bar{c}^2}\left(\frac{\partial}{\partial t} + \bar{u}\frac{\partial}{\partial x_1}\right)^2 - \nabla^2\right) B' = \nabla\cdot(\boldsymbol{\omega}'\times\boldsymbol{u_c})$$

- *D. Yang and A. S. Morgans, in Proceedings of ICSV24, 2017*
- *D. Yang and A. S. Morgans, in Journal of Sound and Vibration, Vol. 393, 2017*
- *D. Yang and A. S. Morgans, in Journal of Sound and Vibration, Vol. 384, 2016*

Annular rig from University of Zaragoza





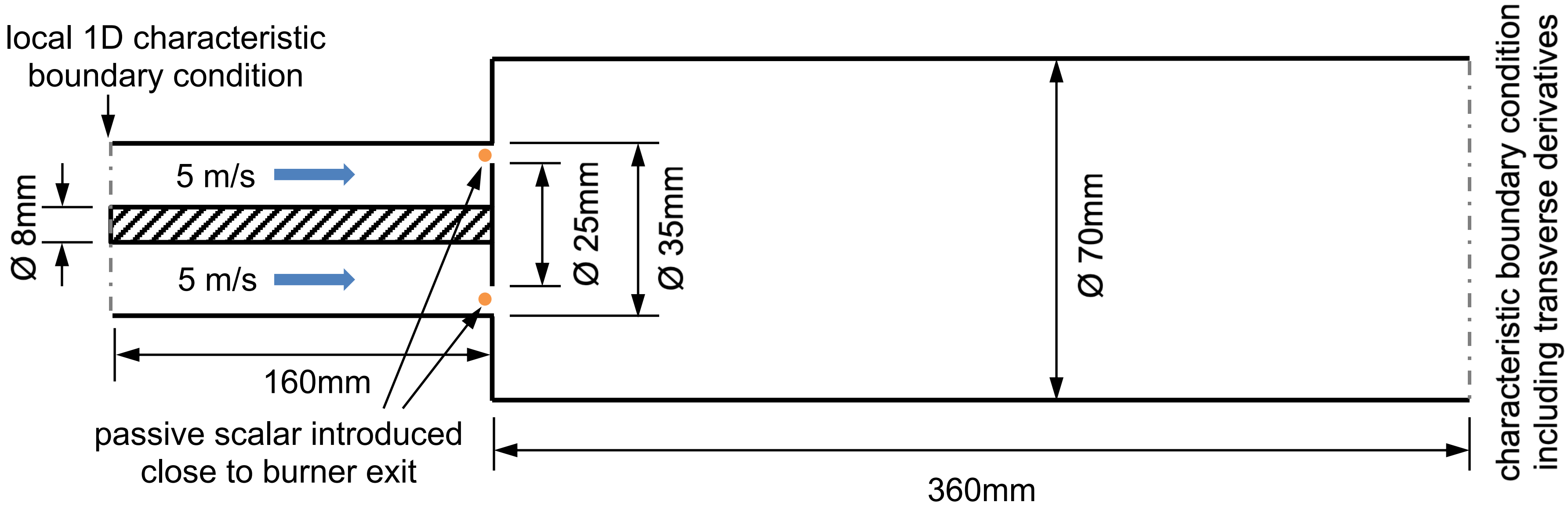
$$\begin{bmatrix} \widetilde{p}_u^- \\ \widetilde{p}_d^+ \end{bmatrix} = \begin{bmatrix} R_{uu} & T_{du} \\ T_{ud} & R_{dd} \end{bmatrix} \begin{bmatrix} \widetilde{p}_u^+ \\ \widetilde{p}_d^- \end{bmatrix}$$

D. Yang and A. S. Morgans, in Proceedings of ICSV24, 2017

Objectives

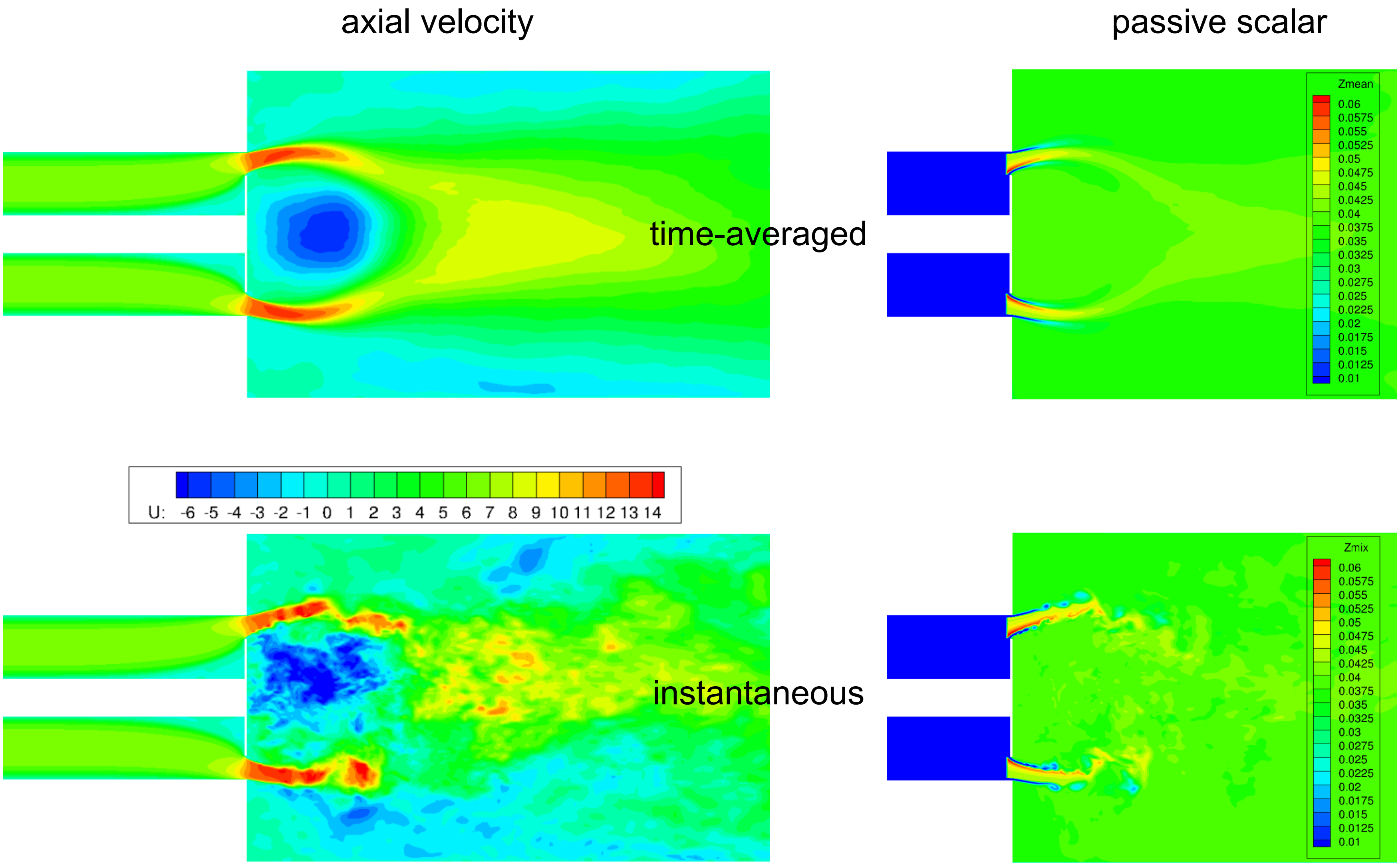
- Validate theoretical model (including quantities which are difficult to access by experiments)
- Examine acoustic-hydrodynamic interactions in terms of large scale structures
- Examine turbulence variation under acoustic perturbations
- Examine transport of passive scalar under periodic perturbations

Numerical setup



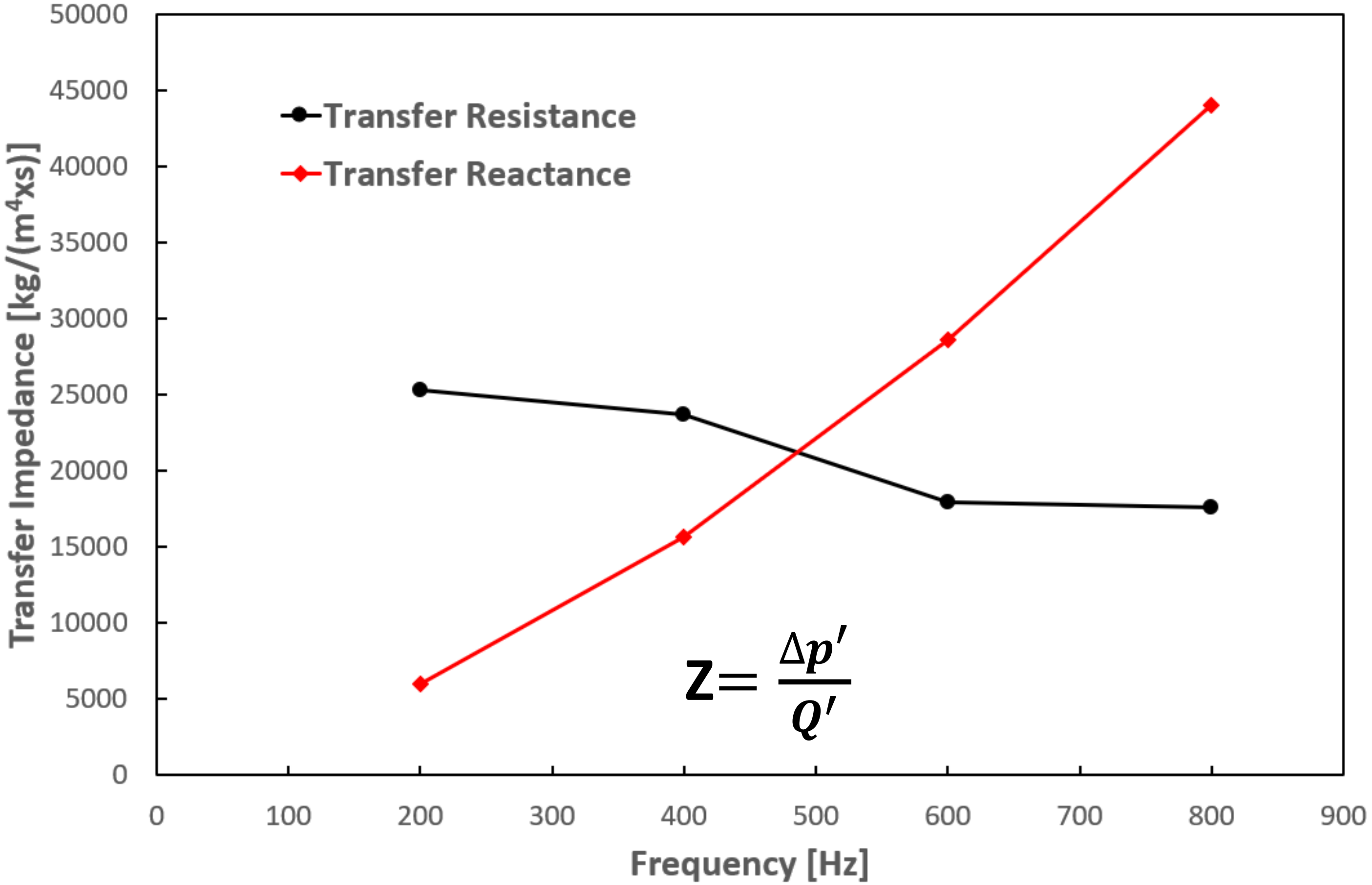
- Modified OpenFOAM compressible rhoPimpleFOAM solver
- Acoustic boundary conditions:
  Inviscid characteristic boundary condition including transverse derivatives
  Yoo and Im, in Combustion Theory and Modelling, 2007
  Su et al., in Proceedings of ASME Turbo Expo, 2015
- LES with WALE model on ~36 million cell grid (>85% of turbulence resolved)
- Additional transport equation for passive scalar with laminar and turbulent Schmidt number equal to 0.7

Base flow

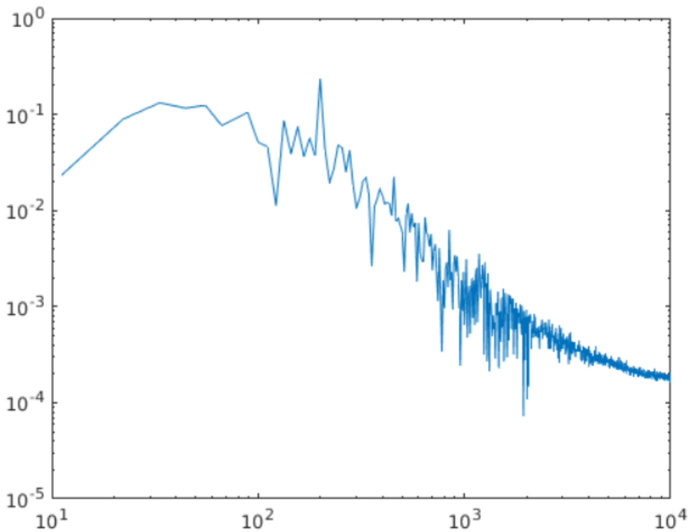

axial velocity
passive scalar
time-averaged
instantaneous
U: -6 -5 -4 -3 -2 -1 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14
Zmean
0.06 0.0575 0.055 0.0525 0.05 0.0475 0.045 0.0425 0.04 0.0375 0.035 0.0325 0.03 0.0275 0.025 0.0225 0.02 0.0175 0.015 0.0125 0.01
Zmix
0.06 0.0575 0.055 0.0525 0.05 0.0475 0.045 0.0425 0.04 0.0375 0.035 0.0325 0.03 0.0275 0.025 0.0225 0.02 0.0175 0.015 0.0125 0.01

Transfer impedance

- Monotone pressure wave of 100Pa 0-to-peak is injected at the inlet.
- Non-reflective boundary condition is applied at outlet.
- Plane waves are determined using multi-microphone technique.

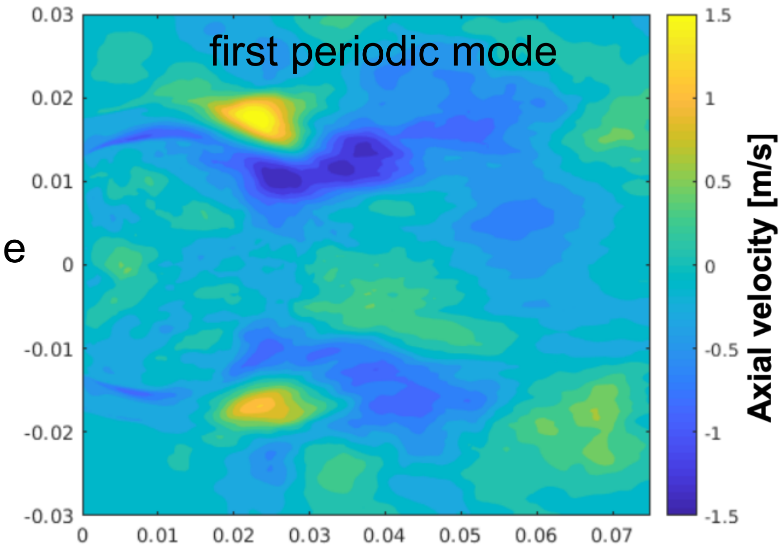


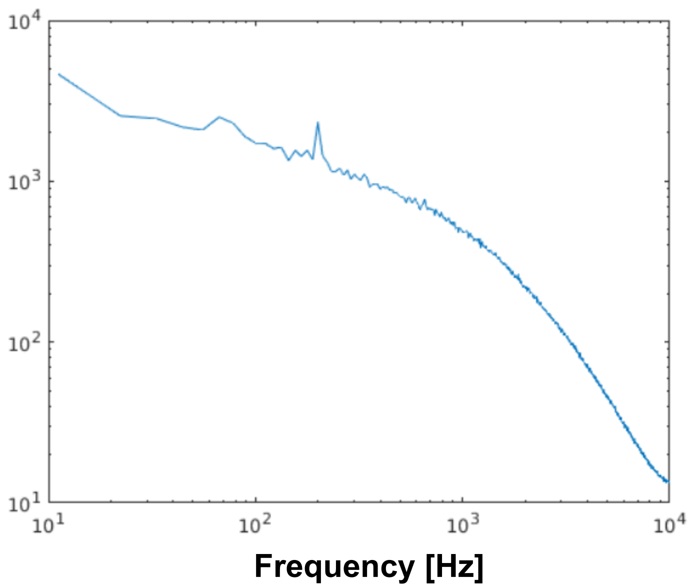
Forced simulation at 200Hz (axial velocity)



POD

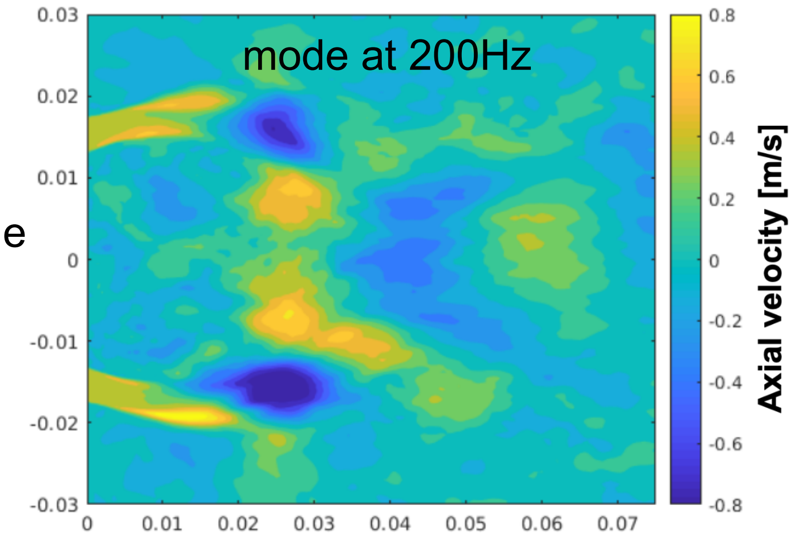
based on in-plane kinetic energy



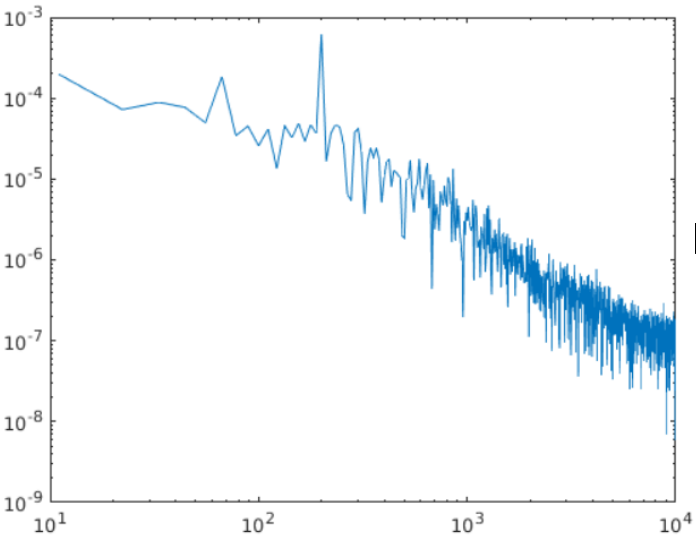


DMD

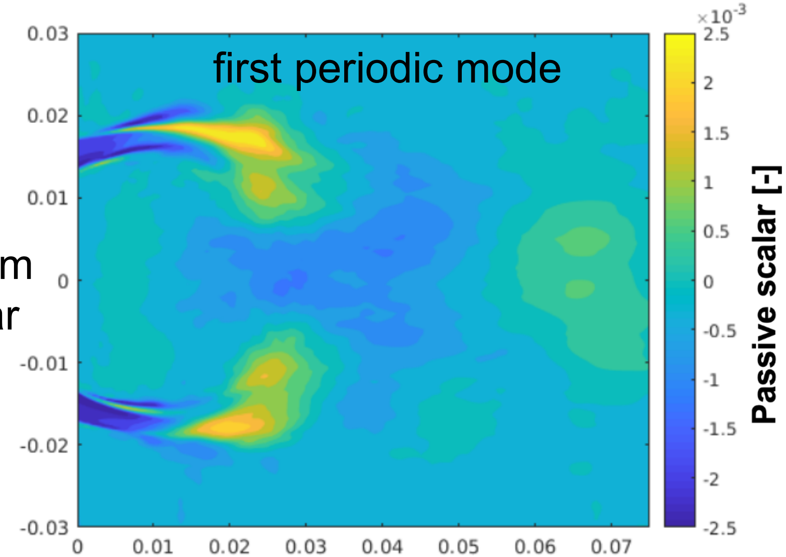
based on in-plane kinetic energy

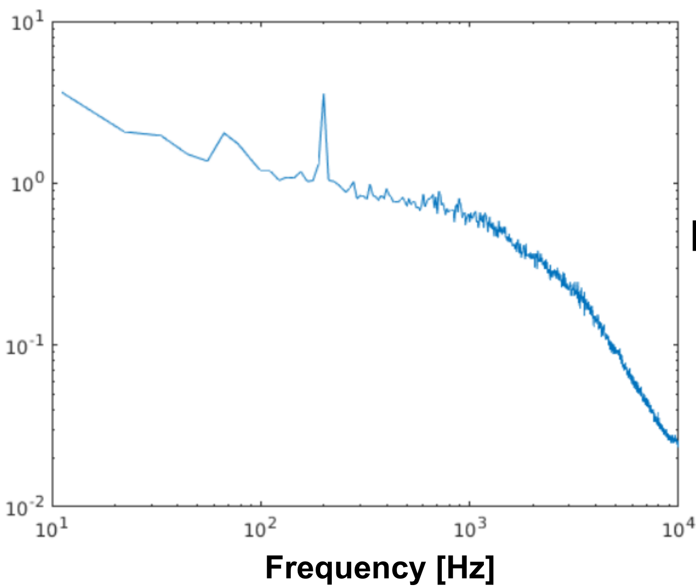


Forced simulation at 200Hz (passive scalar)

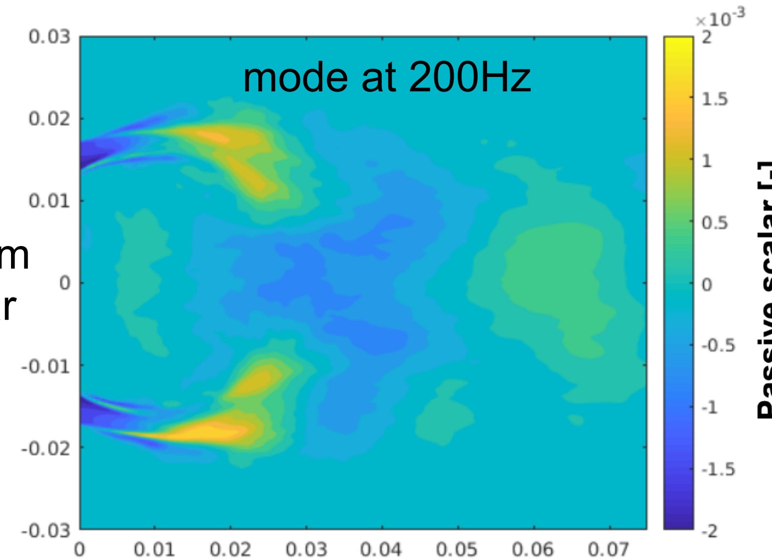


POD
based on L2-norm of passive scalar

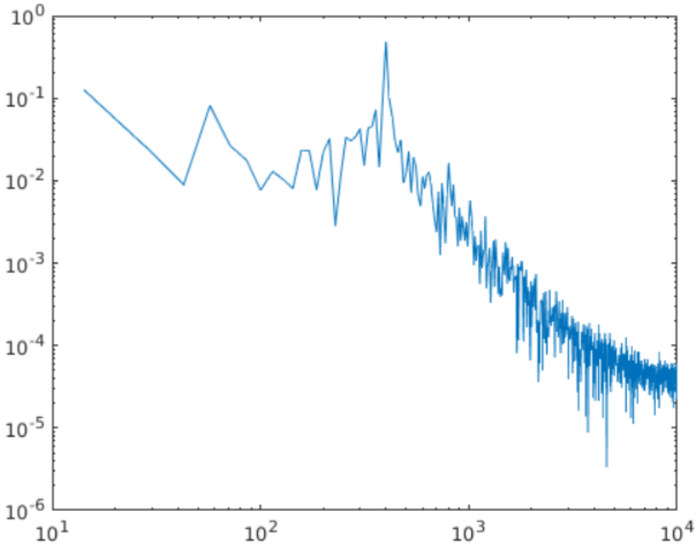




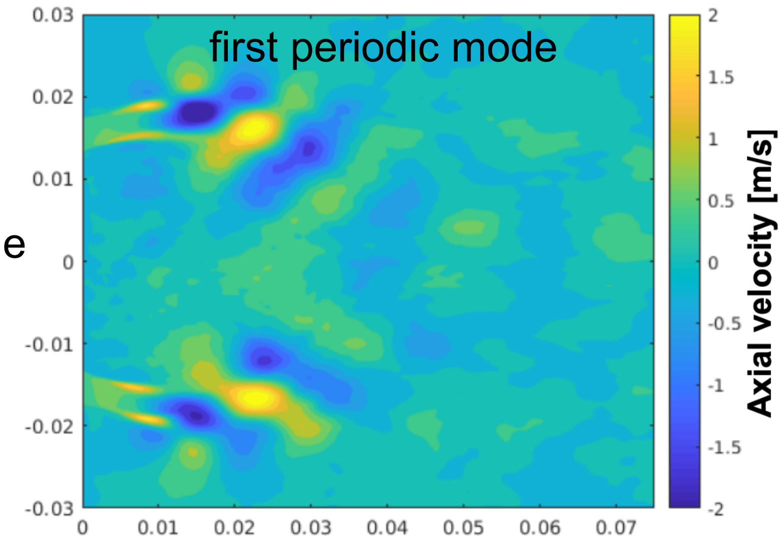
DMD
based on L2-norm of passive scalar

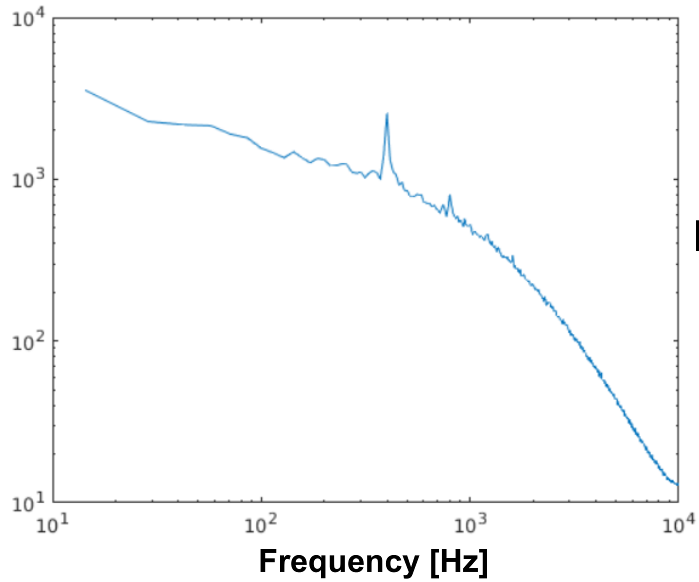


Forced simulation at 400Hz (axial velocity)

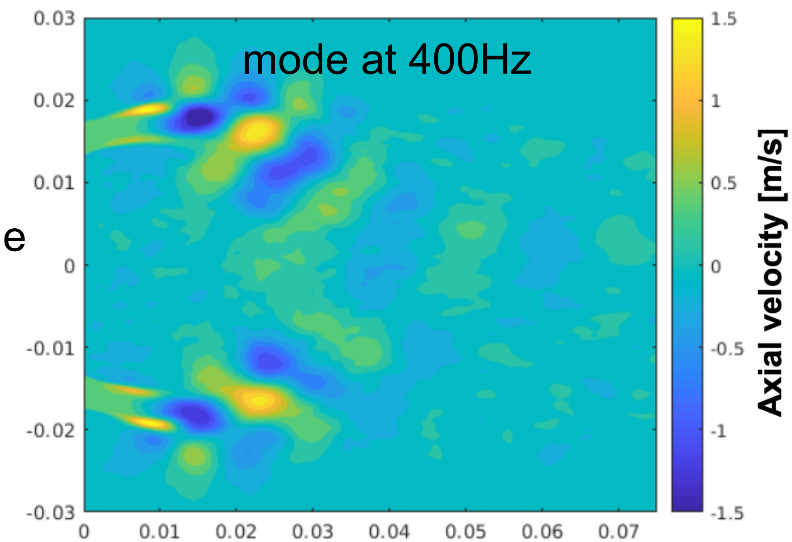


POD
based on in-plane kinetic energy

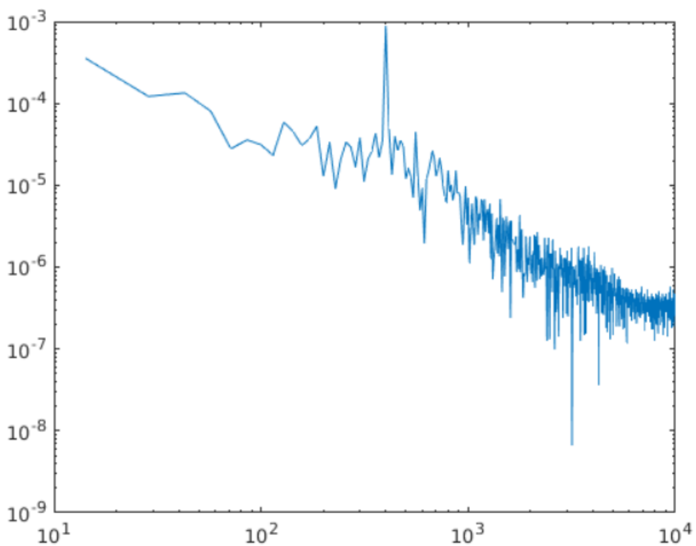




DMD
based on in-plane kinetic energy

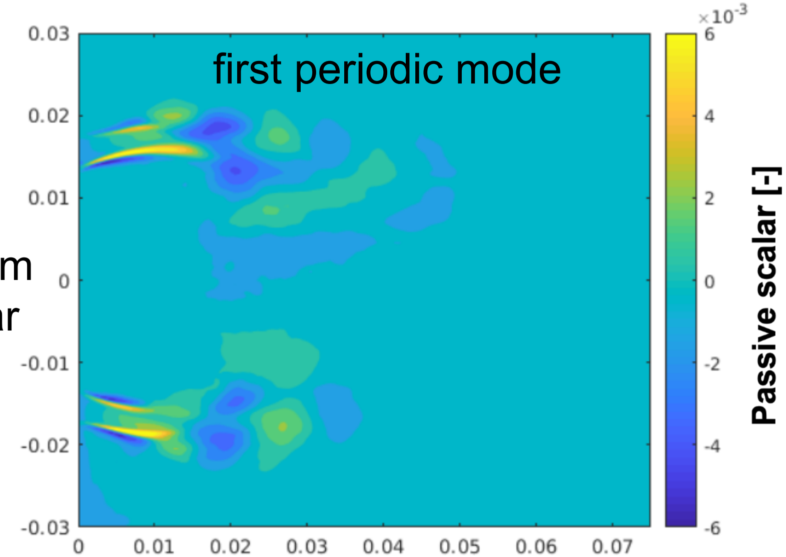


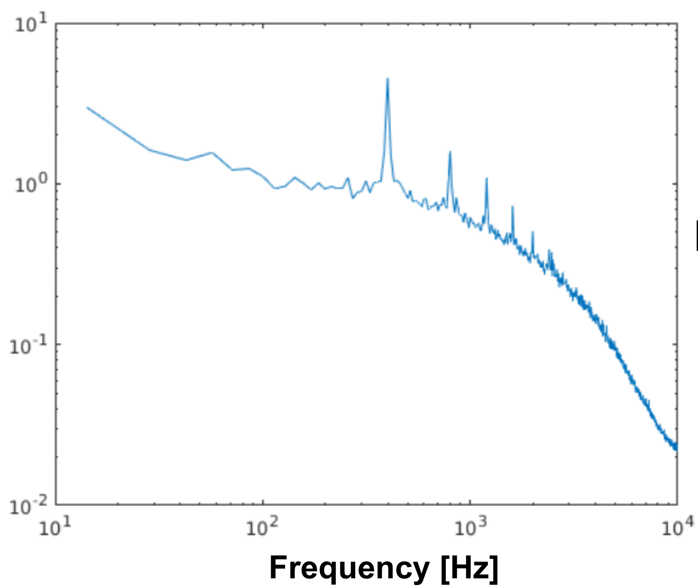
Forced simulation at 400Hz (passive scalar)



POD

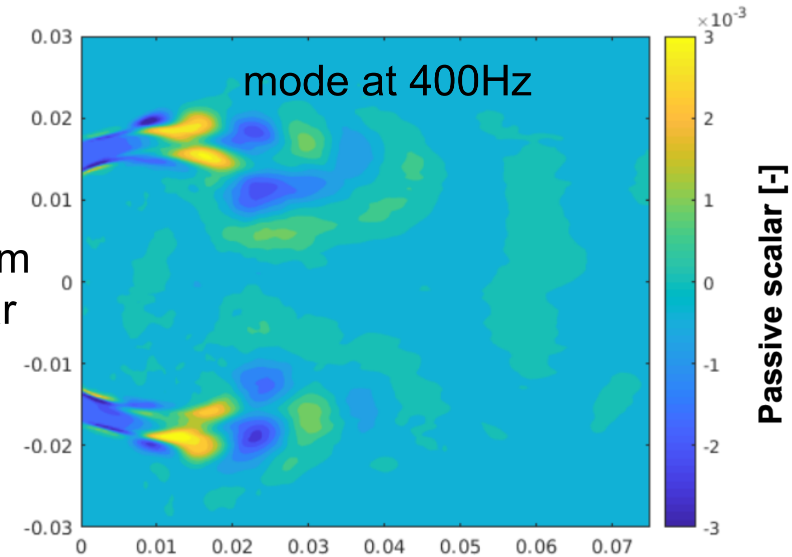
based on L2-norm of passive scalar



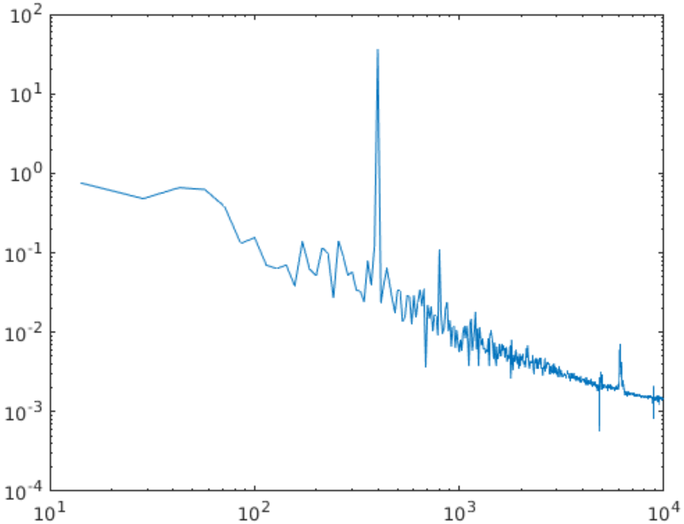


DMD

based on L2-norm of passive scalar

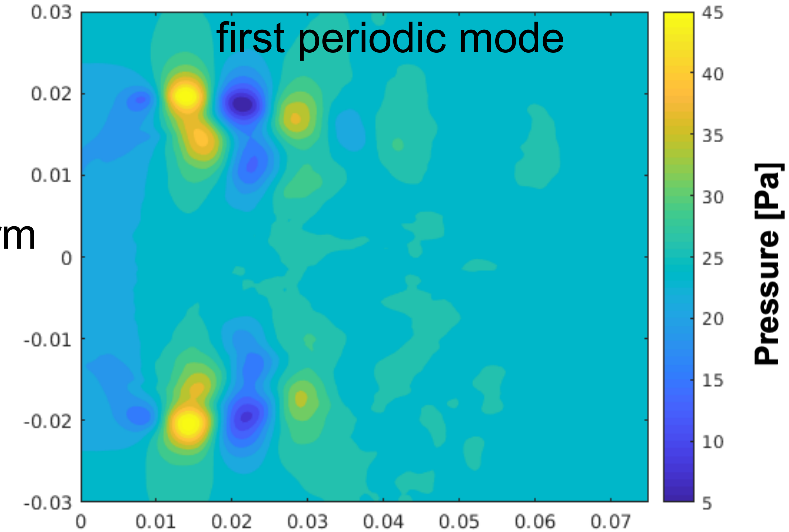


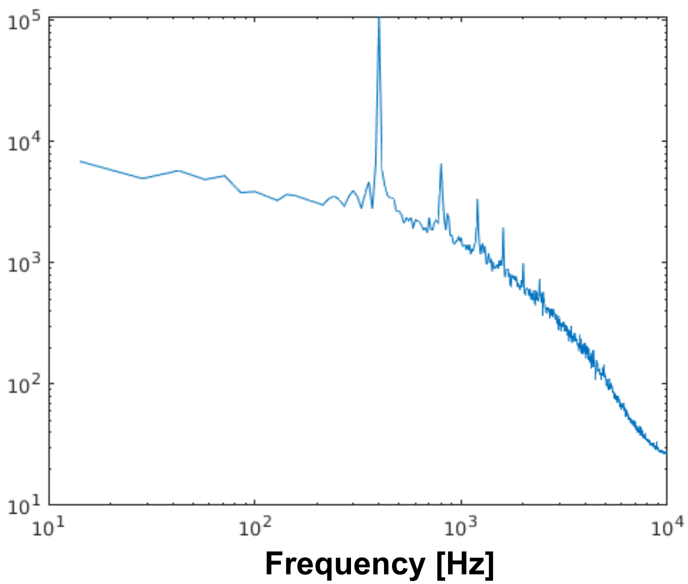
Forced simulation at 400Hz (pressure)



POD

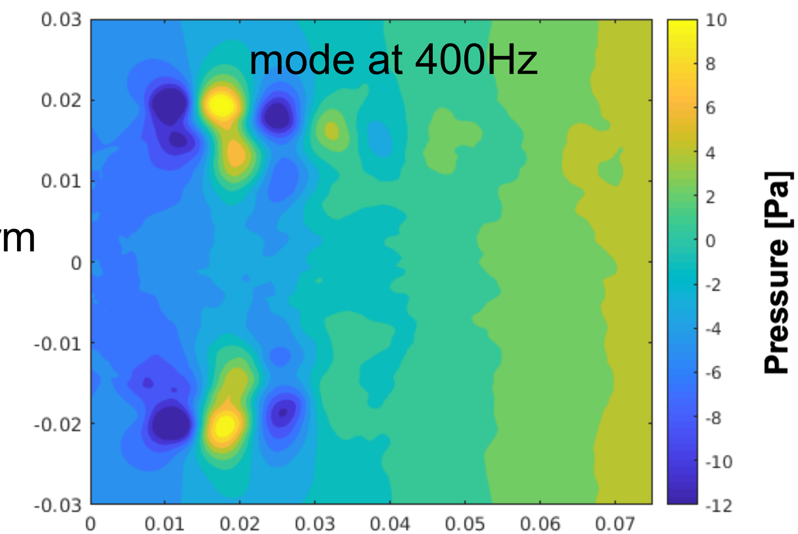
based on L2-norm of pressure





DMD

based on L2-norm of pressure



Imperial College London

Thank you