Identification of wavemaker region in swirling flows using complex network analysis

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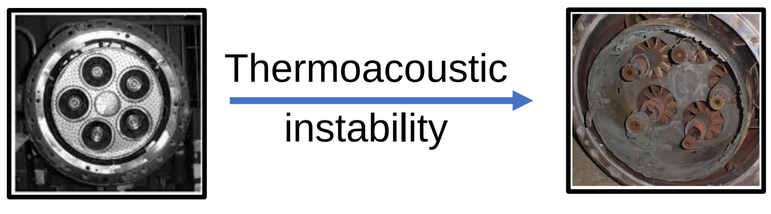
INTRODUCTION



[1]

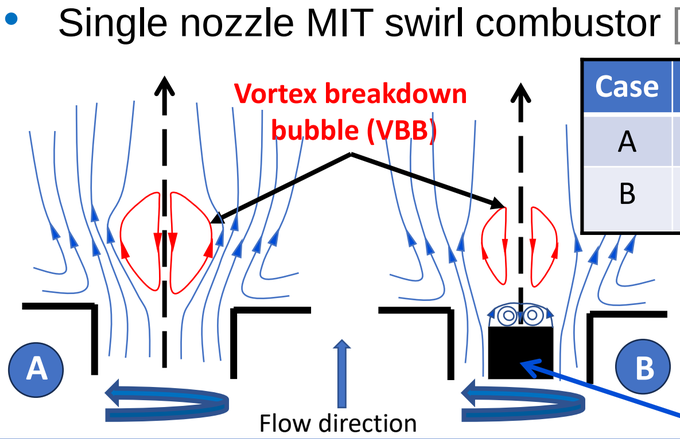
- **Precessing vortex core (PVC)** oscillations in swirl nozzle flows can induce/suppress thermoacoustic instability

Motivation:

- Physics based linear stability analysis
  - Requires accurate base flow
  - Not straightforward for complex geometries
- Data-driven alternatives like **complex network analysis**

Investigated configuration:

- Single nozzle MIT swirl combustor [2]



Case	f_{pvc}	Type
A	128 Hz	Coherent
B	104 Hz	Intermittent

Bulk velocity, $U_b = 8\ ms^{-1}$
$(Re \sim 20{,}000)$
Swirl, $S = 0.67$

Centrebody ($D_c = 9.5\ mm$)

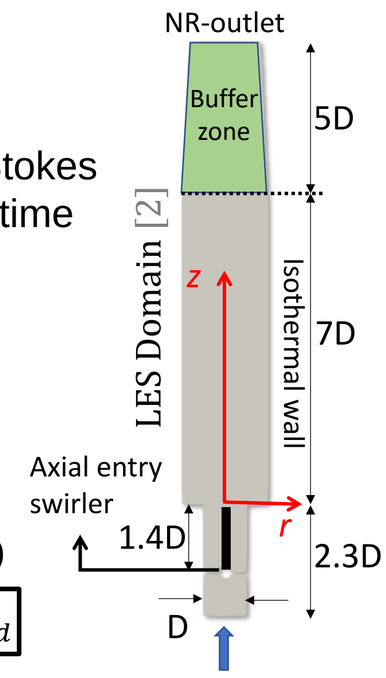
METHODS

Large Eddy Simulation:

- **Explicit filtering LES** [3] for compressible Navier-Stokes
- 8^{th} order central difference (spatial), 3^{rd} order RK in time
- Time series data sampled at $20\ kHz$

Linear Stability Analysis:

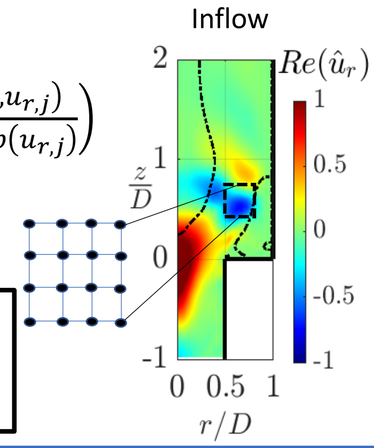
- Constant density, linearized Navier-Stokes eq.
- Base flow from LES
  - Axisymmetric mean flow
  - Turbulent transport model - Eddy-viscosity (ν_T)
- Generalized eigenvalue problem $\mathbf{A}\{\bar{Q}\}\hat{q}_{m,d} = \omega\mathbf{B}\hat{q}_{m,d}$



Complex network analysis (CNA):

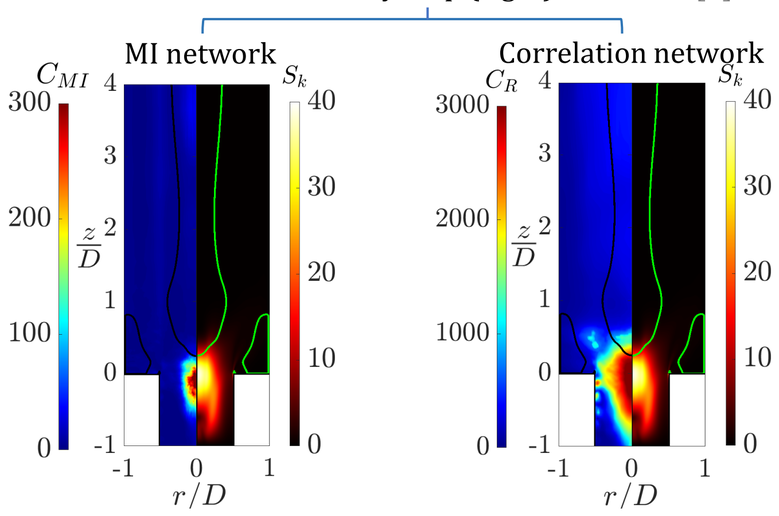
- Connectivity:
  - **Mutual info. (MI)**, $M_{ij} = \sum_{i,j} p(u_{r,i}, u_{r,j}) \log_2 \left(\frac{p(u_{r,i}, u_{r,j})}{p(u_{r,i})p(u_{r,j})} \right)$
  - **Correlation,** $R_{ij} = \frac{Cov(u_{r,i}, u_{r,j})}{\sigma(u_{r,i})\sigma(u_{r,j})}$
- **Weighted closeness centrality** [4] used to rank nodes

$$C_i = \sum_{j=1, j\neq i}^{N} 2^{-d_{ij}}$$

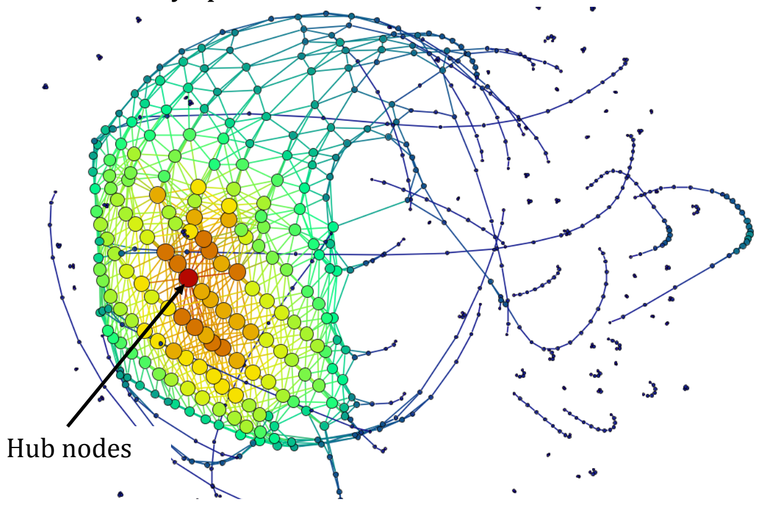


RESULTS & DISCUSSION

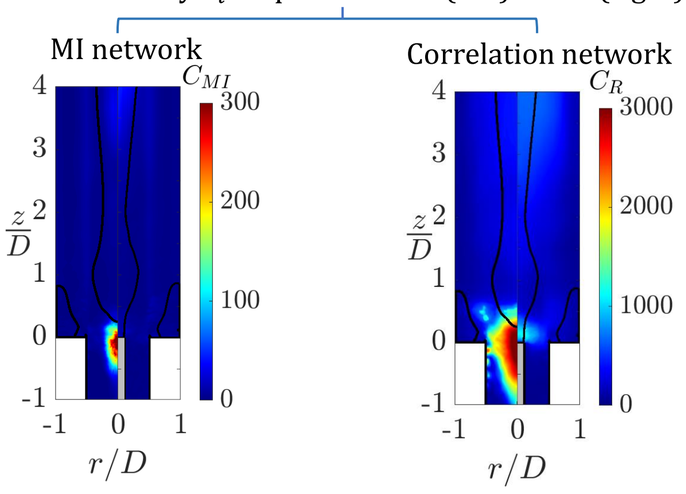
Centrality C_i map (left) compared with structural sensitivity map (right) for case A [5]



Heavily sparsified MI network for case A



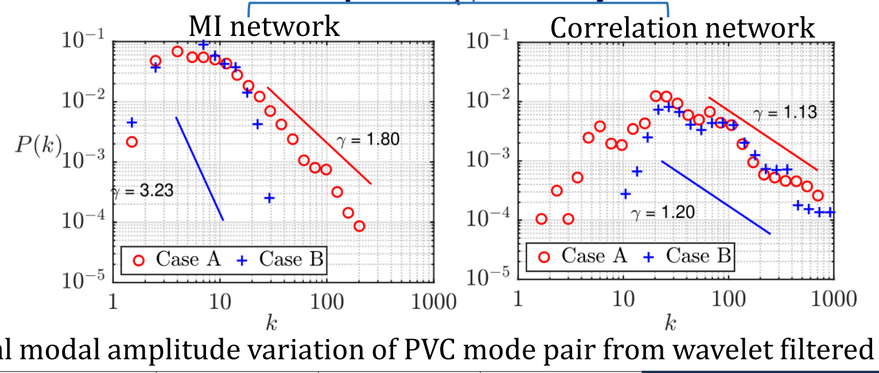
Centrality C_i maps for case A (left) and B (right)



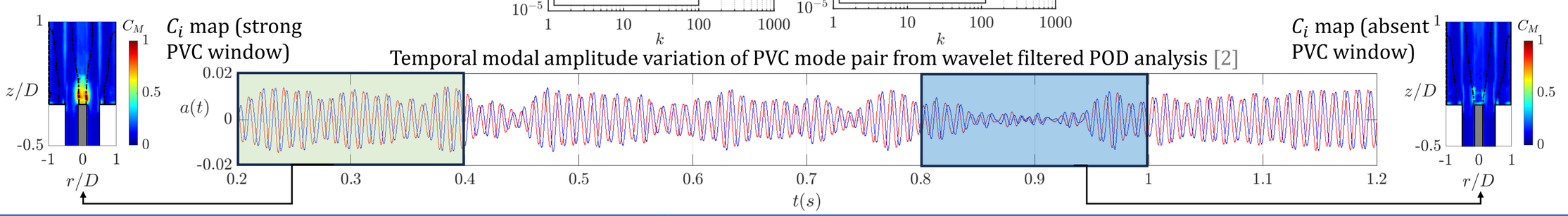
- **Small-world** behavior in the presence of PVC
- **Scale-free** otherwise

$$P(k) \propto k^{-\gamma}$$

Weighted degree distribution



- Presence of distinct network hub in case A extending into the nozzle.
- Weakening of the PVC captured by vanishing hubs of windowed networks.



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CONCLUSIONS

- Linear stability and network analyses identify the PVC wavemaker region.
- MI networks fare better than correlation networks in recovering wavemaker spatial extents.
- Intermittent suppression of PVC in the centrebody case marked by reduction in closeness centrality.
- Future work: Use causal measures (e.g. transfer entropy) in CNA, build a theoretical framework for CNA, validate with canonical flow studies.

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