A Proper Orthogonal Decomposition based Reduced Order Model for Vortex-Induced Vibrations

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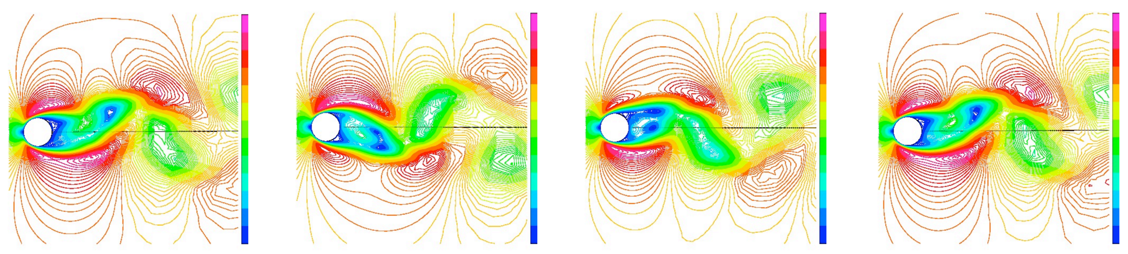
Research Objective

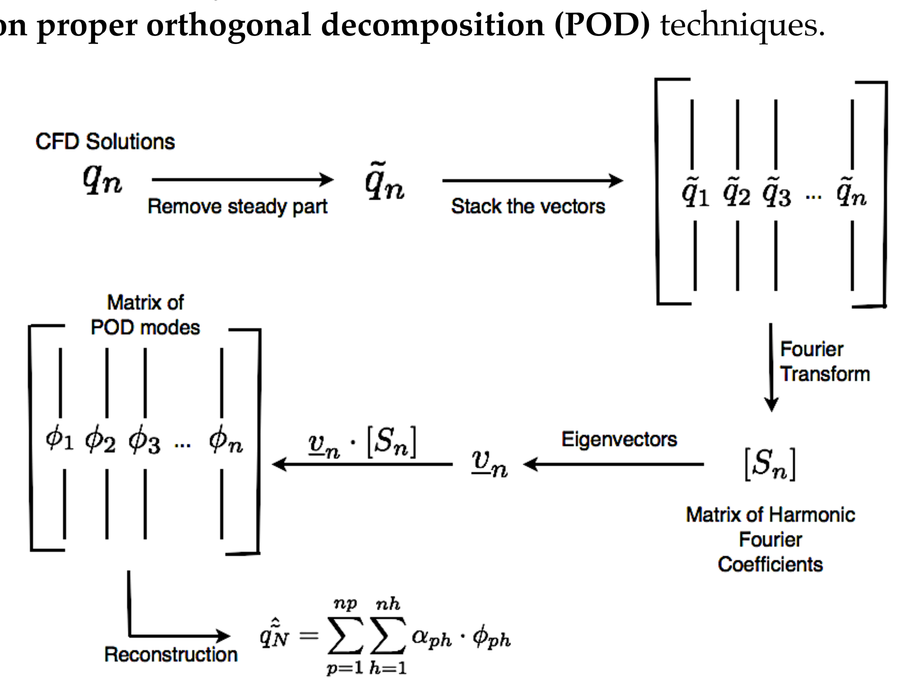
- Flow passing by a cylinder induces **shedding vortices** (shown below), leading to "vortex-induced vibrations."



- If the cylinder is forced to oscillate, the shedding frequency and the oscillation frequency may **lock in**. Large-amplitude oscillations develop and induce **fatigue** and eventually, **structural failure**.
- Example of frequency lock-in: **offshore platforms** (water flowing over a pipe), **turbomachinery** (aerodynamic instabilities in jet-engine compressors), and **airplane-wing performance** (buffet).
- **OBJECTIVE:** Building a reduced-order model to predict locked-in solutions without running computationally expensive CFD simulations.

Method

- **GOAL**: Using locked-in solutions from a Harmonic Balance (HB) computational fluid dynamics (CFD) code to built a **reduced-order model based on proper orthogonal decomposition (POD)** techniques.



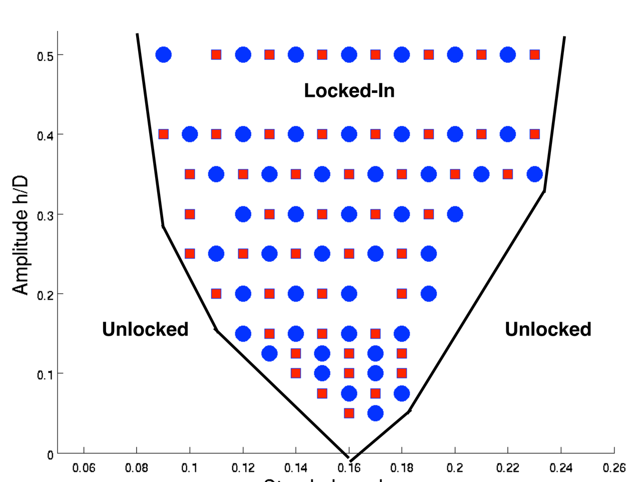


Figure 1: CFD solutions for a cylinder in cross flow at Reynolds = 120.
The lock-in region is V-shaped.
Within the lock-in region, the blue circles represent the CFD solution set used to form the POD modes.
The red squares are the solutions to be predicted.

Conclusions and Future Work

- This research presents a novel way of **accurately predicting locked-in CFD solutions with a reduced order model to help prevent the failure of structures**
- Converged, locked-in CFD solutions from a HB algorithm can be used as basis functions (or **snapshots**) to form the POD modes of the reduced-order model.
- With the right choice of CFD snapshots, accurate CFD solutions may be predicted using a **very small number of POD modes** (fewer than six).
- CFD solutions are successfully predicted for a **cylinder** as well as for **2D and 3D compressor blades.**
- The reduced-order model will be extended to other **turbomachinery applications.**

Acknowledgments

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References:

1. Hall, K.C., Thomas, J.P., and Dowell, E.H., Reduced-Order Modeling of Unsteady Small-Disturbance Flows using a Frequency-Domain Proper Orthogonal Decomposition Technique, AIAA Journal, 2000, pp.1853-1862
2. Anagnostopoulos, P., and Bearman, P., Response Characteristics of a Vortex-Excited Cylinder at Low Reynolds Numbers, Journal of Fluids and Structures, 1992, pp. 39-50.
3. Williamson, C. H. and Givardhan, R. (2004), "Vortex-Induced Vibrations," in Annual Review of Fluid Mechanics.

Two POD Modes Dominate The Flow Field

- The first two POD modes tend to dominate the complete flow field.
- Additional POD modes contribute to the overall vortex-shedding.

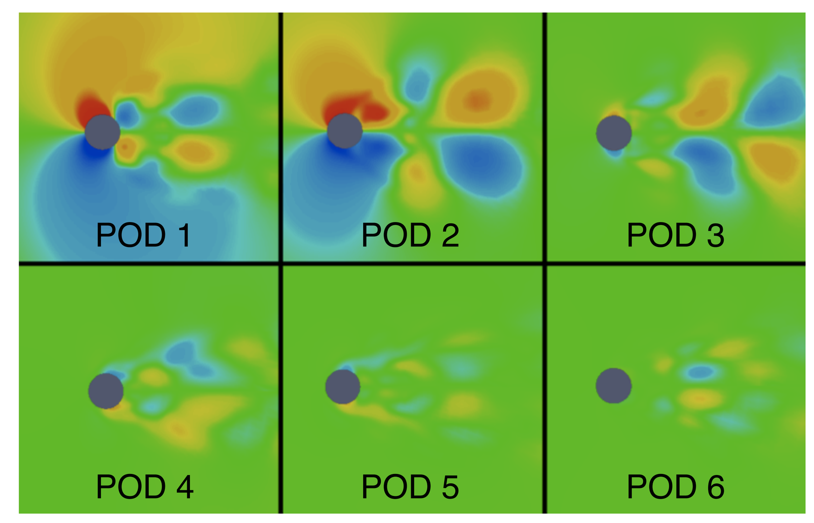


Figure 2: Unsteady pressure contours of the first harmonic for the first six POD modes. Each POD mode shows a decreasing contribution to the instability in the flow field around the cylinder.

- The first two POD modes have the largest eigenvalues, thus contain most of the flow field energy.

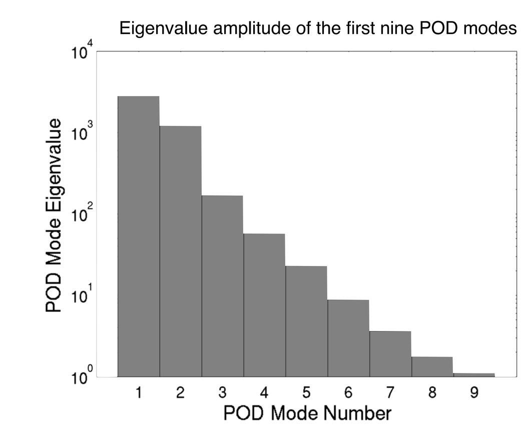


Figure 3: Eigenvalues of the first nine POD modes of the first harmonic. The first two eigenvalues are an order of magnitude larger.

- Modal Amplitudes α's are interpolated for each harmonic and each POD mode using least square methods

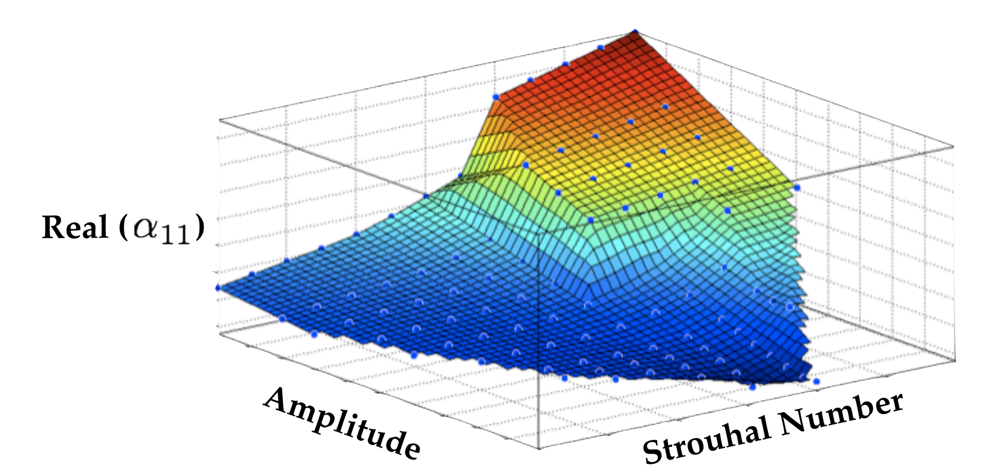


Figure 4: The real part of the modal amplitude shows sharp variations throughout the lock-in region. This surface will be fit by a two variable, fifth order polynomial.

CFD Predictions With Six POD Modes Are Accurate

- Visualization of the flow around the oscillating cylinder:
  - The main features of the flow are well described using only two POD modes.
  - Six POD modes are necessary to capture smaller details.

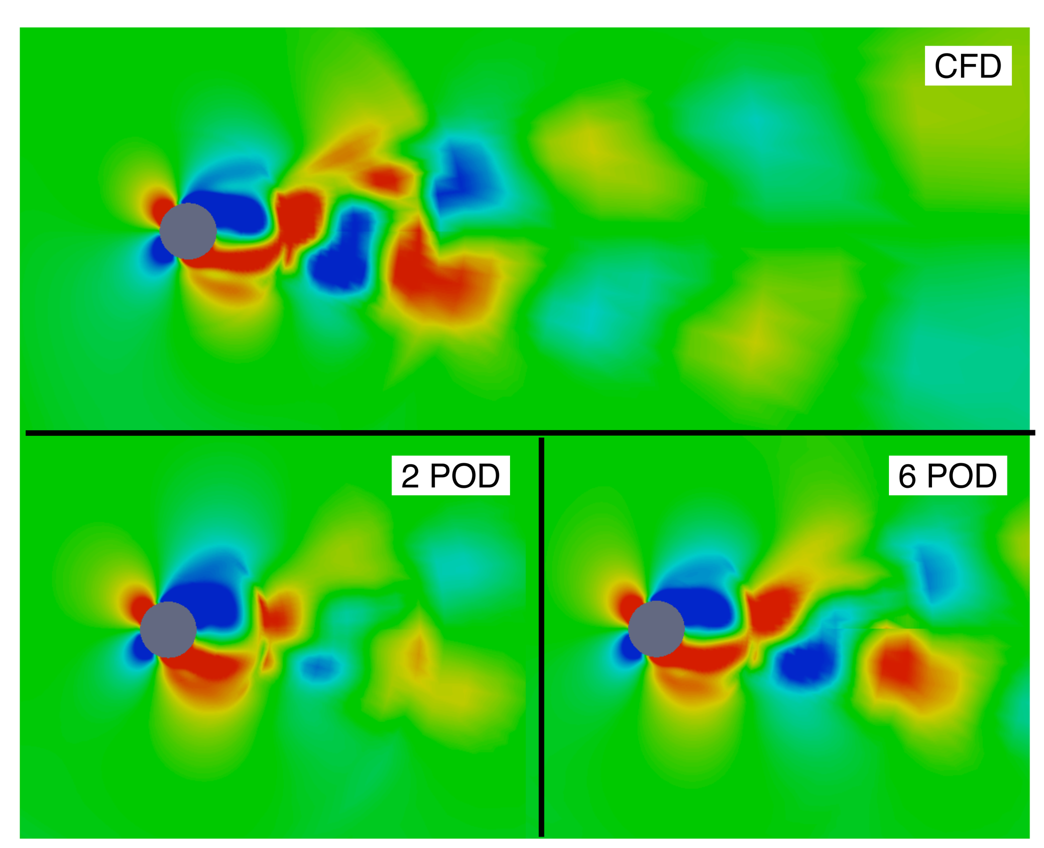


Figure 5: Unsteady pressure contours show the reconstruction of the CFD solution using different numbers of POD modes.
The top figure shows the original CFD simulation solution.
The bottom left and bottom right figures show the reconstructed flow field using two and six POD modes, respectively.

- Comparison of the unsteady surface pressure between the original CFD solution and the predicted solution:
  - The general shape of the pressure curves is well captured with as few as two POD modes.
  - The quality of the surface pressure prediction improves with the number of POD modes.

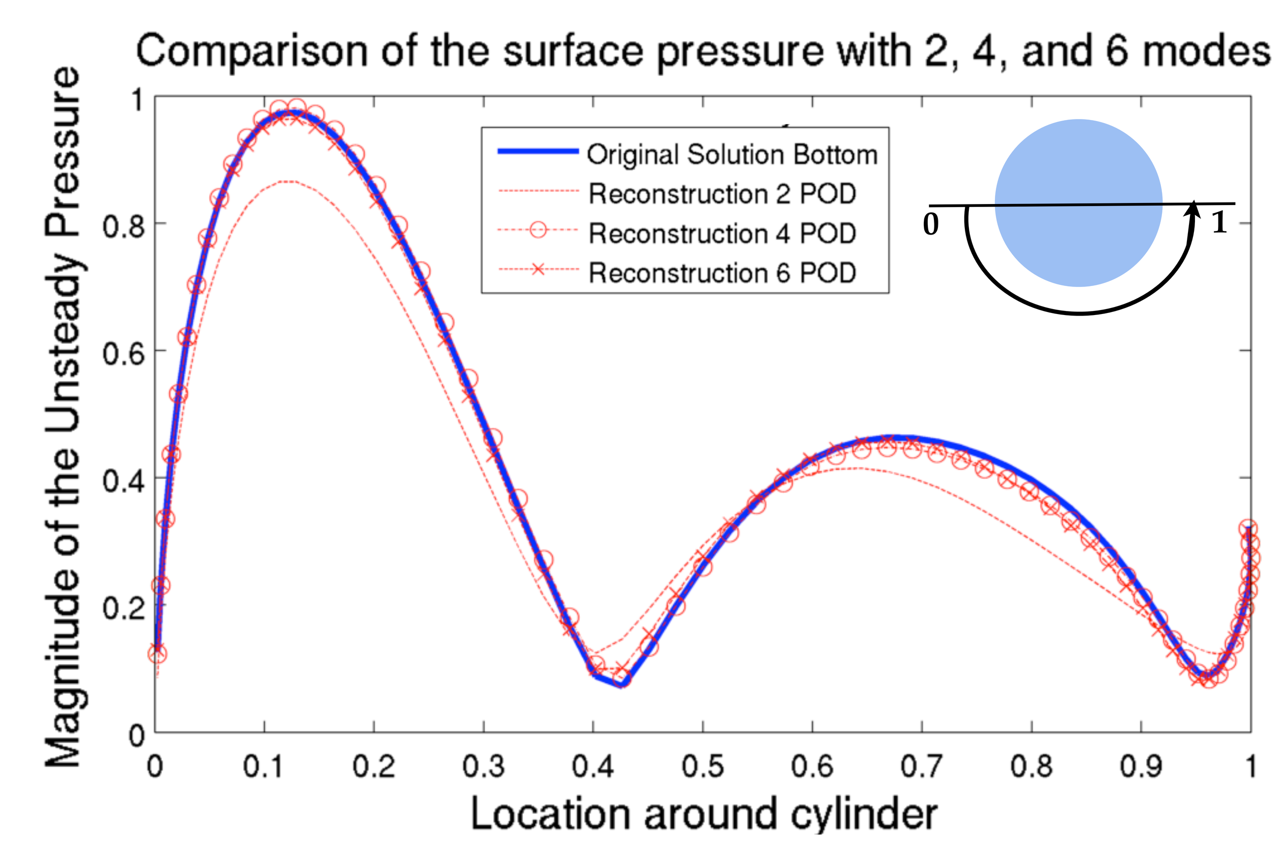


Figure 6: Surface pressure on the bottom of the cylinder. The blue curve represent the surface pressure given by the CFD solution. The red curves represent the predicted surface pressure with two, four, and six POD modes.

Reduced Order Model Is Extended Across Multiple Variables

- Unsteady pressure contours show that at least six POD modes are necessary to capture the basic flow features of a CFD reconstruction across Reynolds numbers

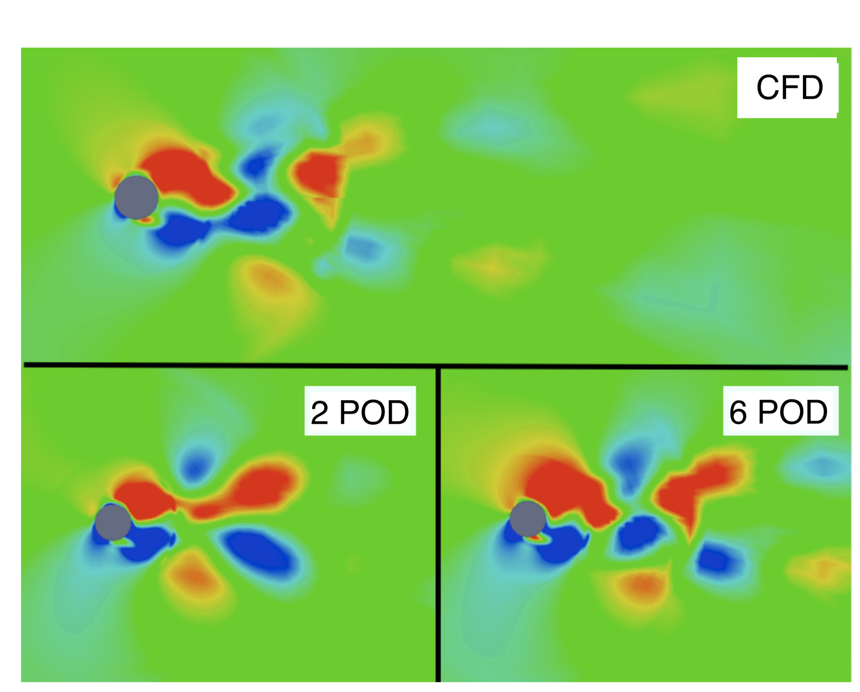


Figure 7: Unsteady pressure contours show the reconstruction of a CFD solution at Re = 130. The top figure shows the original CFD simulation solution.
The bottom left and bottom right figures show the reconstructed flow field using two and six POD modes.

- Surface pressure reconstruction are not as accurate as within a set of solutions from one Reynolds number
- More POD modes are necessary to compensate the additional degree of freedom (i.e. Reynolds number)

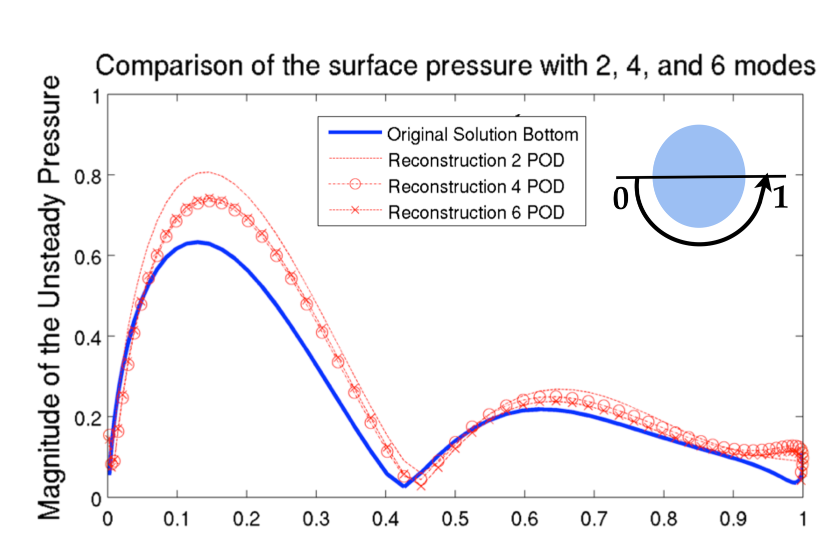
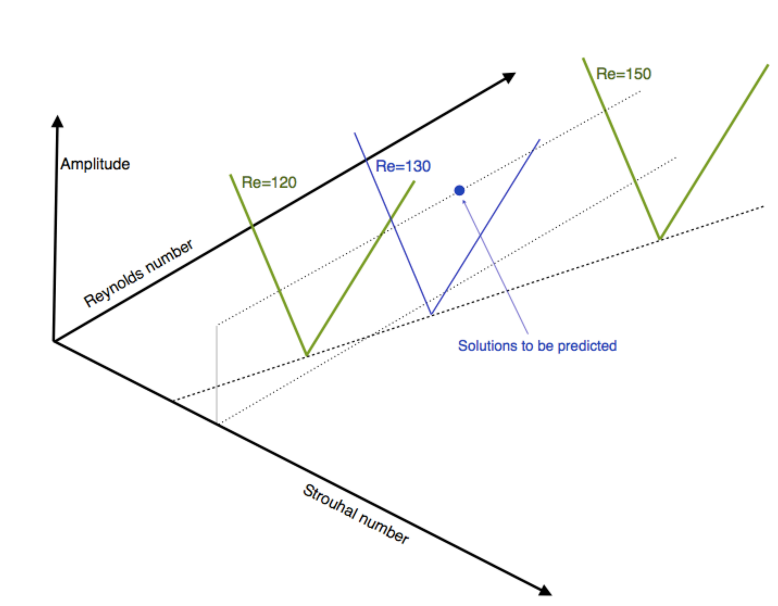


Figure 8: Surface pressure on the bottom of the cylinder. The blue curve represent the surface pressure given by the CFD solution at Re = 130. The red curves represent the predicted surface pressure with two, four, and six POD modes.

- The reduced-order uses the CFD solution sets from Re=120 and Re=150 to construct the POD modes.
- Modal Amplitudes α's are predicted at a different Reynolds number using a three variable least square method
- Solutions at Re=130 are predicted.



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