Development and assessment of POD for analysis of turbulent flow in piston engines

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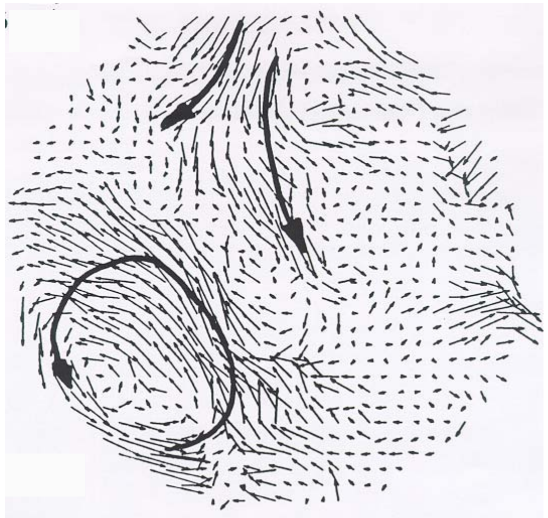
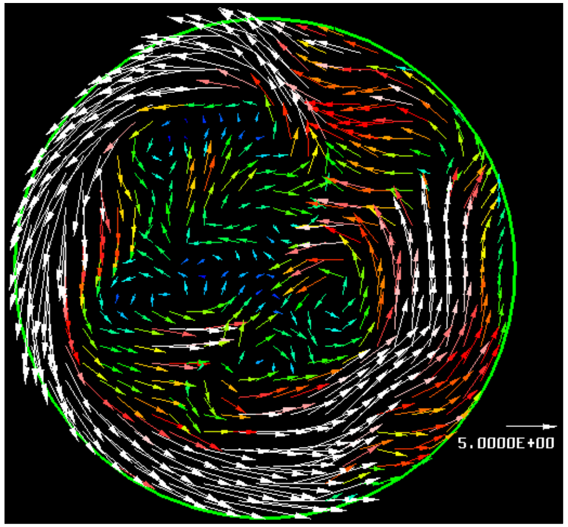
Premise:

Proper orthogonal decomposition (POD) can reveal physical insight into in-cylinder flow dynamics. POD also can provide an objective basis for quantitative comparisons between high-spatial-and-temporal-resolution optical diagnostics (PIV) and numerical simulations (LES).

PIV (Reuss 1998)



LES (Haworth 1999)



POD has been applied to in-cylinder flows for over 10 years

- Key Features
  - A turbulent flow can be expressed as a linear combination of POD modes
  - Each POD mode is itself a 2D or 3D flow field
  - POD modes are mutually orthogonal
  - A larger fraction of the flow's kinetic energy can be captured using fewer POD modes compared to any other orthogonal basis
- Early Applications to Flows in IC engines
  - Borée et al. (1999) Eur. Ser. Appl. Ind. Math. 7:56-65.
  - Raposo et al. (2000) 10^{th} Intern'l. Symp. Appl. Laser Diag. Tech. Fluid Mech.
  - Borée et al. (2002) Phys. Fl. 14:2543-2556.
  - Erdil et al. (2002) FTaC 68:91-110.
  - Fogleman et al. (2004) JoT 5:23.
- Further Information
  - Holmes, Lumley and Berkooz (1996) *Turb., Coh. Struc., Dyn. Syst. &Symm.*

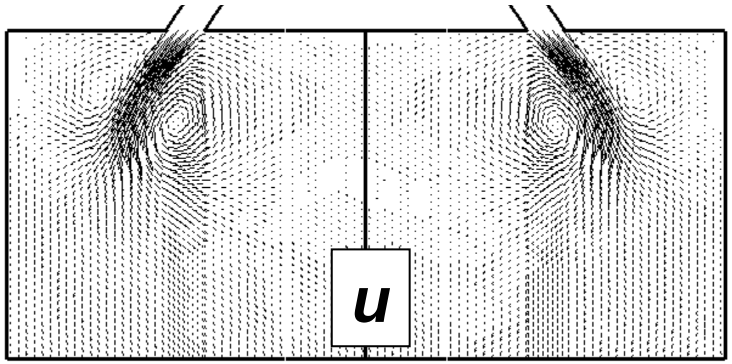
Most applications of POD have employed the method of snapshots*

- Overview
  - Starting point: a sequence of *M* instantaneous velocity fields (“snapshots”)
  - Each snapshot: 2 or 3 velocity components at *N* discrete spatial locations
  - Spatial locations are arbitrary, but must be the same for all snapshots
  - *M* POD modes are obtained by solving an eigenvalue/eigenvector problem; modes are ordered by decreasing kinetic energy
- “Phase-Dependent” POD
  - All snapshots are at the same crank position
  - Each snapshot corresponds to a different engine cycle
- “Phase-Invariant” POD (Fogleman et al. 2004)
  - Snapshots may be from different crank positions
  - Three transformations are applied:
    - Linear spatial transformation so that velocities are at same spatial locations for all snapshots
    - Linear velocity transformation to retain the global 1D velocity divergence
    - Velocity rescaling so that each snapshot has the same kinetic energy

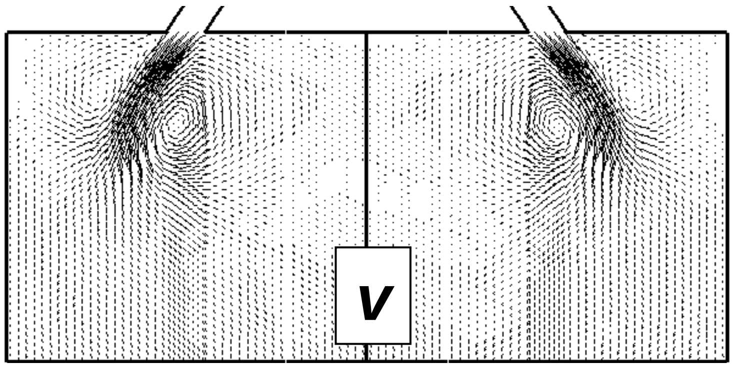
*Sirovich (1987) Quart. Appl. Math. 45:561-590

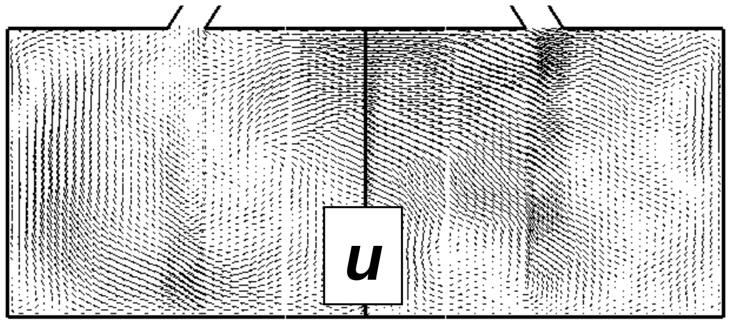
Objective criteria are required to quantify the degree to which two velocity fields are similar or dissimilar

$$f \equiv \frac{(\boldsymbol{u},\boldsymbol{v})}{\|\boldsymbol{u}\|\|\boldsymbol{v}\|}$$

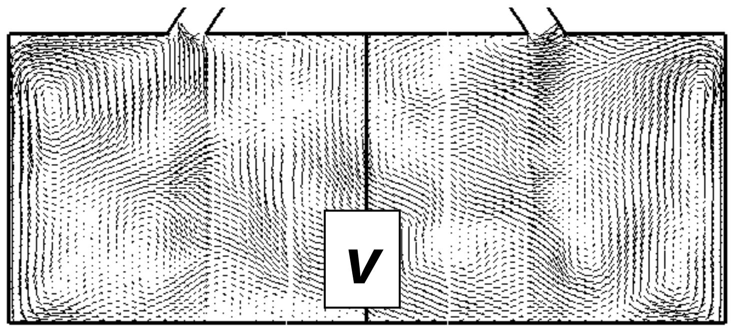


f = 0.998



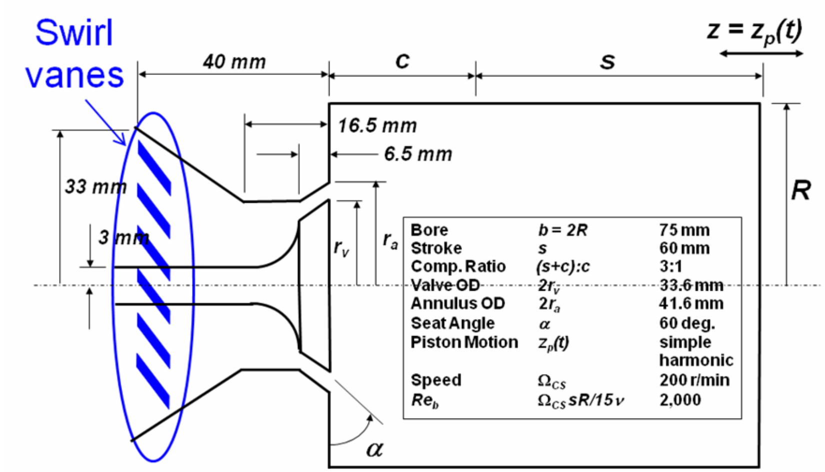


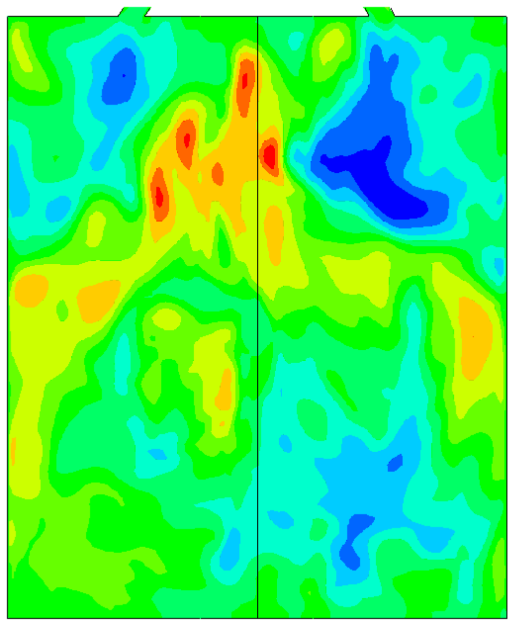
f = 0.302



Here POD is performed on datasets generated using LES

- Axisymmetric Piston-Cylinder Assembly With and Without Swirl
  - Morse et al. (1978) Imperial College FS/78/24
- STAR-CD v4
- ~Second-Order Spatial and Temporal Discretizations
- One-Equation Subfilter-Scale Turbulence Model
- ~1.3M cells
- 30-50 Cycles
- Up to 360 Snapshots per Cycle
- Liu and Haworth (2010) FTaC 85



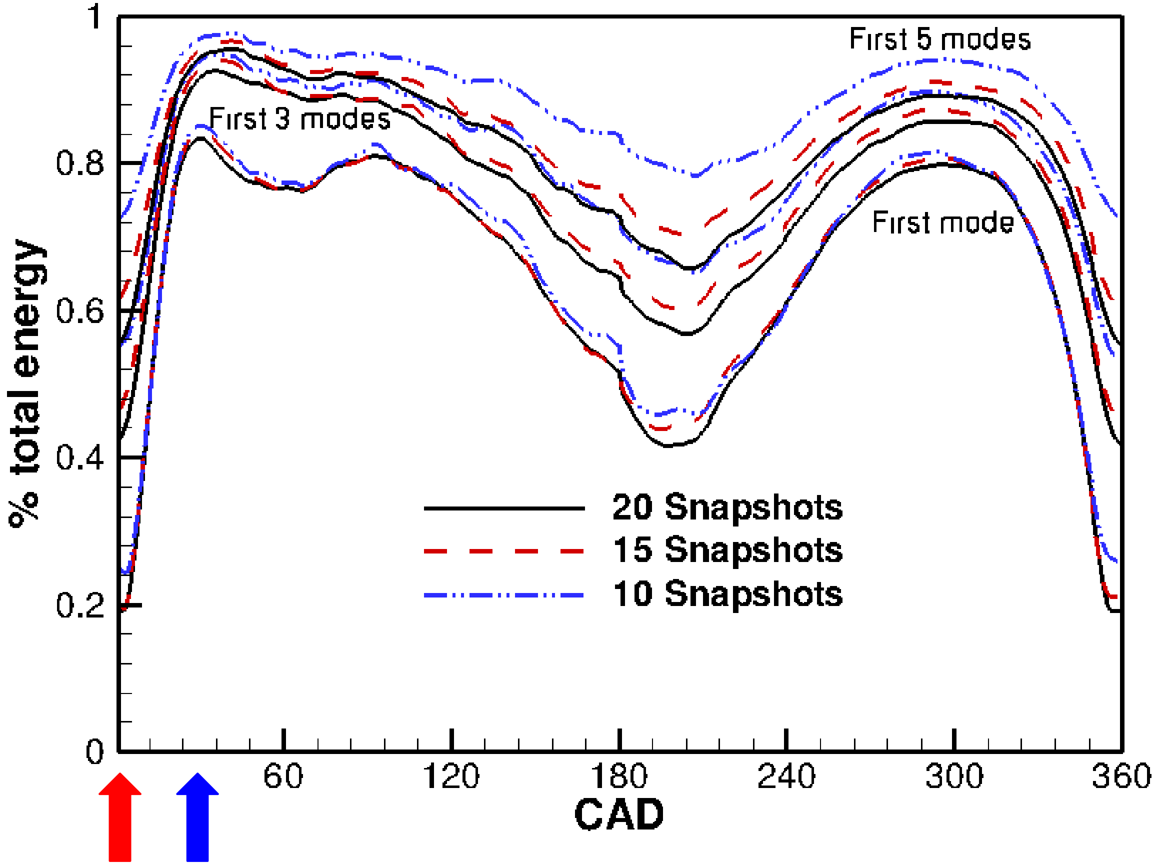


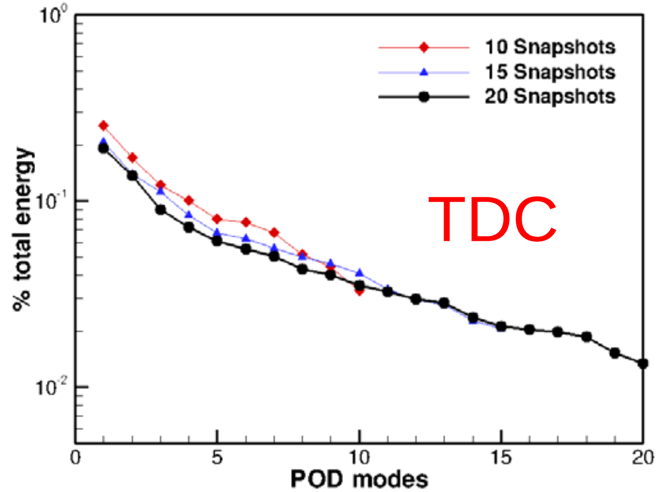
A systematic and comprehensive parametric study has been performed to explore POD for in-cylinder flows*

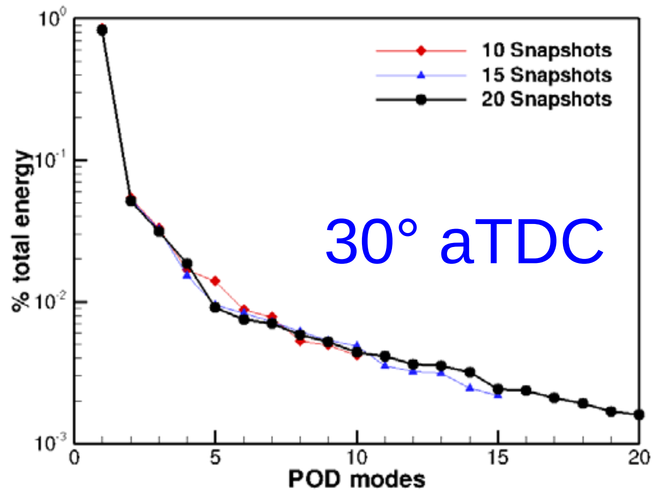
- Phase-Dependent vs. Phase-Invariant
- 2D vs. 3D
- Interpolated vs. Raw Velocity Data
- Subtracting vs. Not Subtracting Ensemble Average
- Full vs. Reduced Field of View
- Influence of Number of Cycles
- Influence of Number of Snapshots per Cycle
- Influence of Transformations (Phase-Invariant POD)
- Quantification of Cycle-to-Cycle Variations
- Swirling vs. Nonswirling Flow

*Liu and Haworth (2011) SAE World Congress, submitted

2D phase-dependent POD is the natural choice for phase-locked planar PIV data

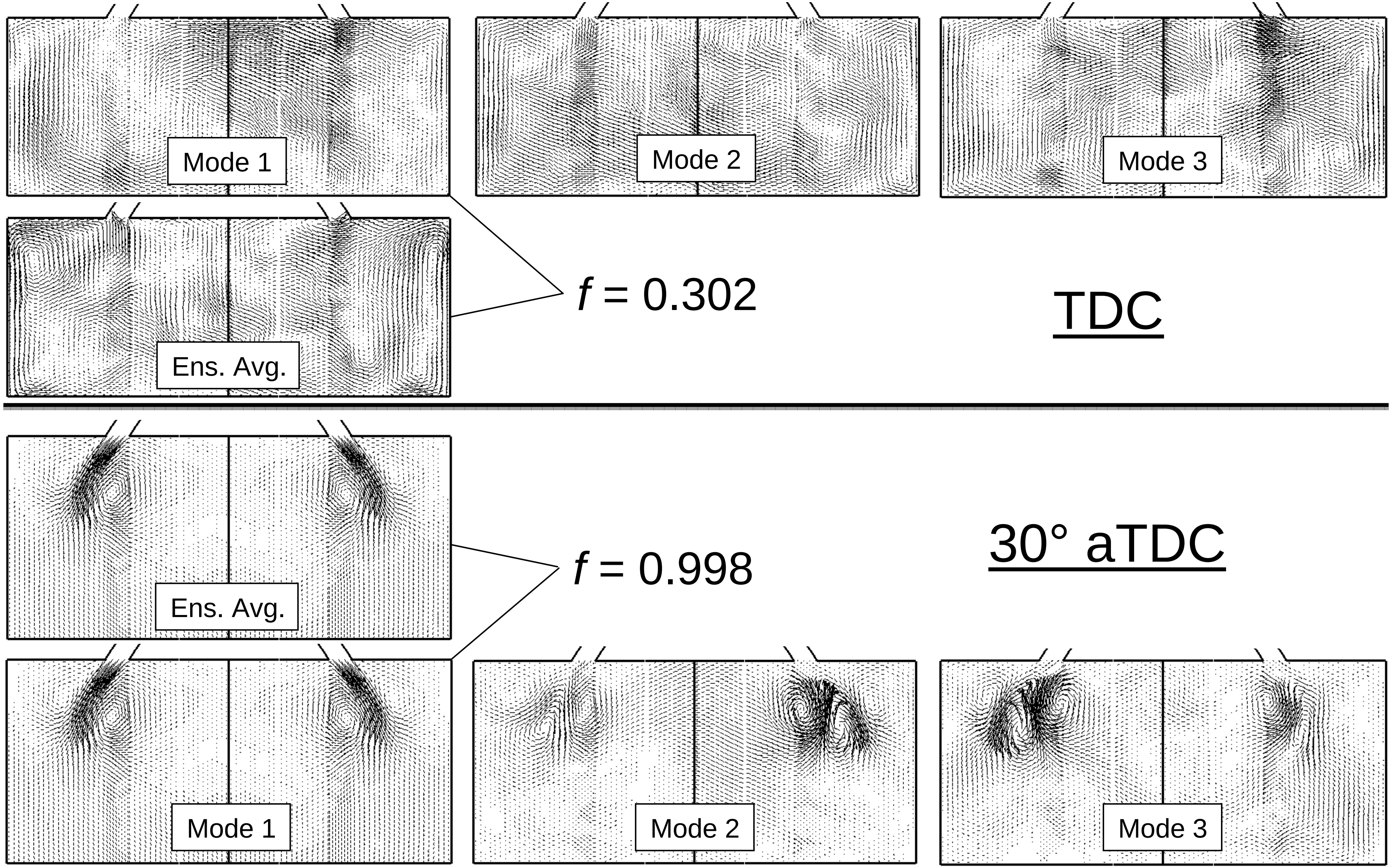






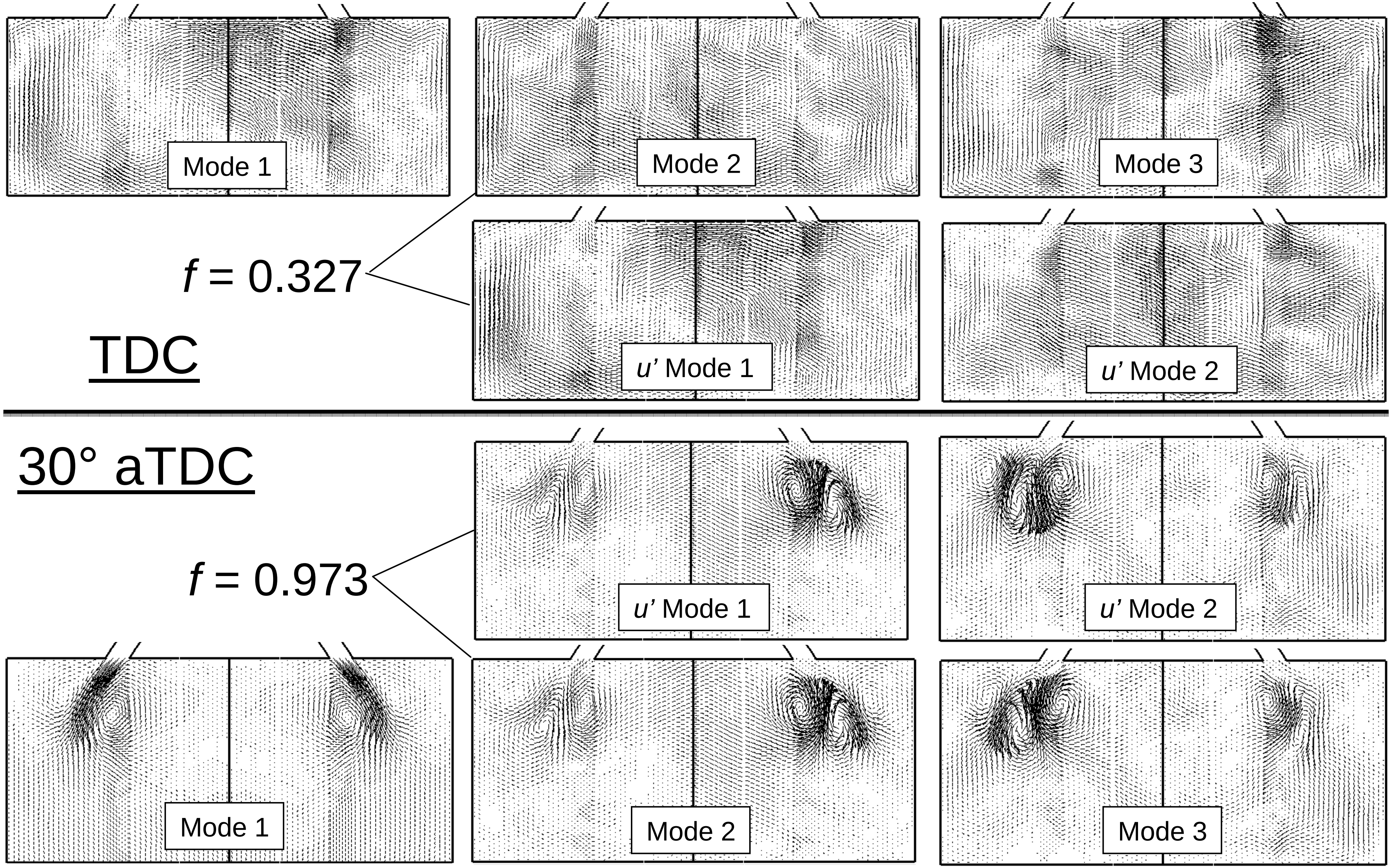
2D phase-dependent POD, cutting plane containing cylinder axis, nonswirling case

2D phase-dependent POD (cont.)



2D phase-dependent POD, cutting plane containing cylinder axis, nonswirling case

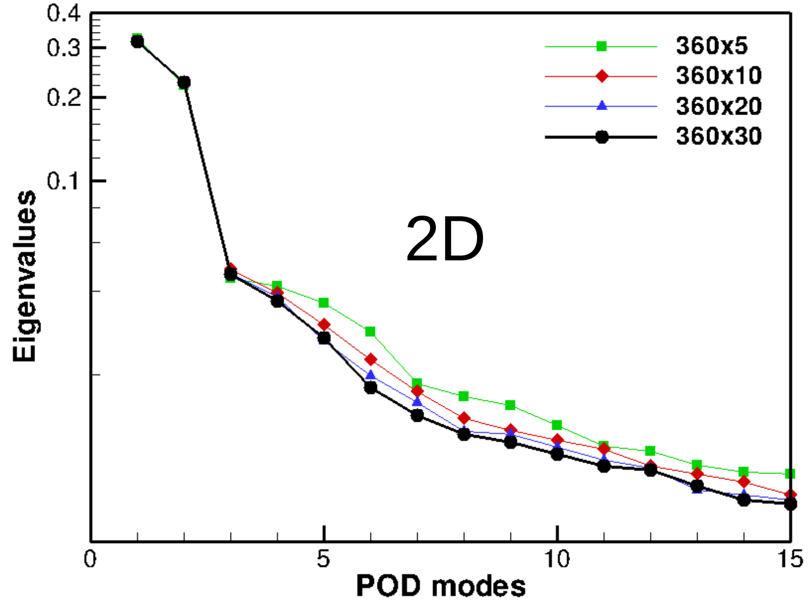
2D phase-dependent POD (cont.)



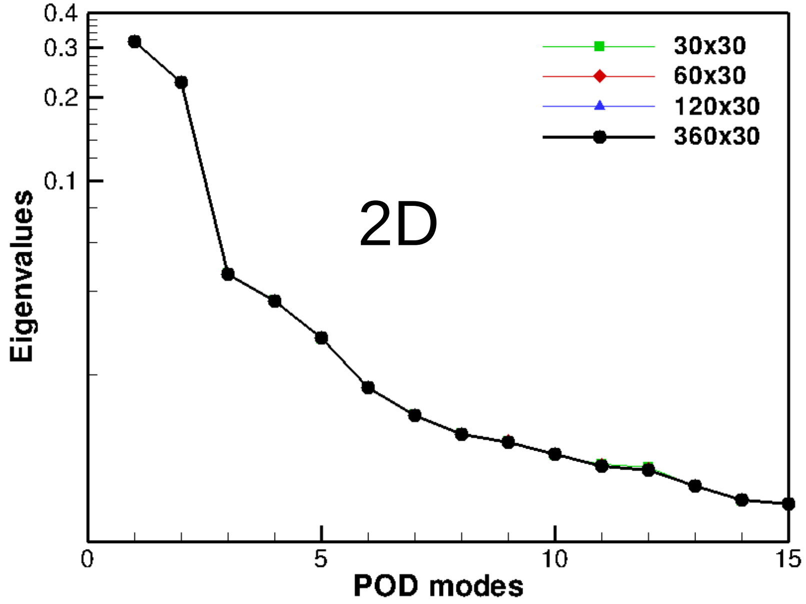
2D phase-dependent POD, cutting plane containing cylinder axis, nonswirling case

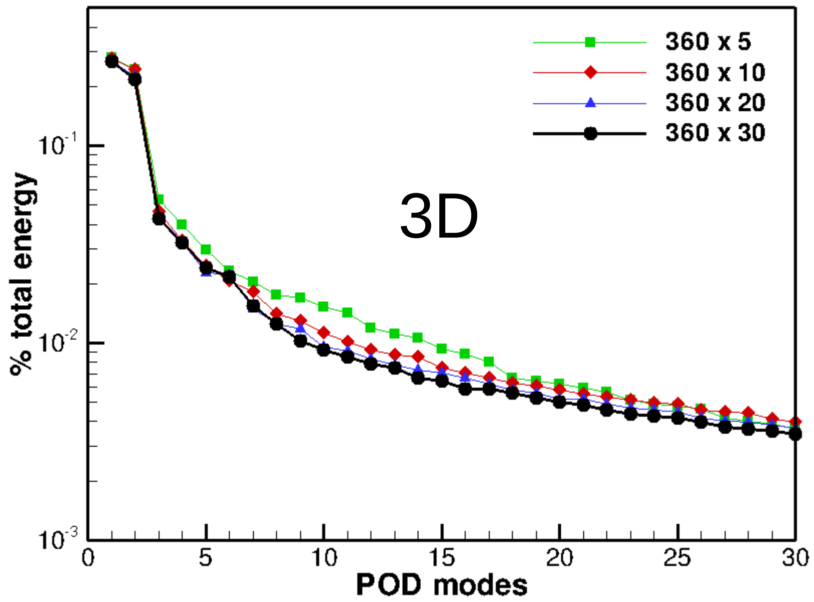
Phase-invariant POD represents the flow through full engine cycles

360 phases used,
variation in number of cycles



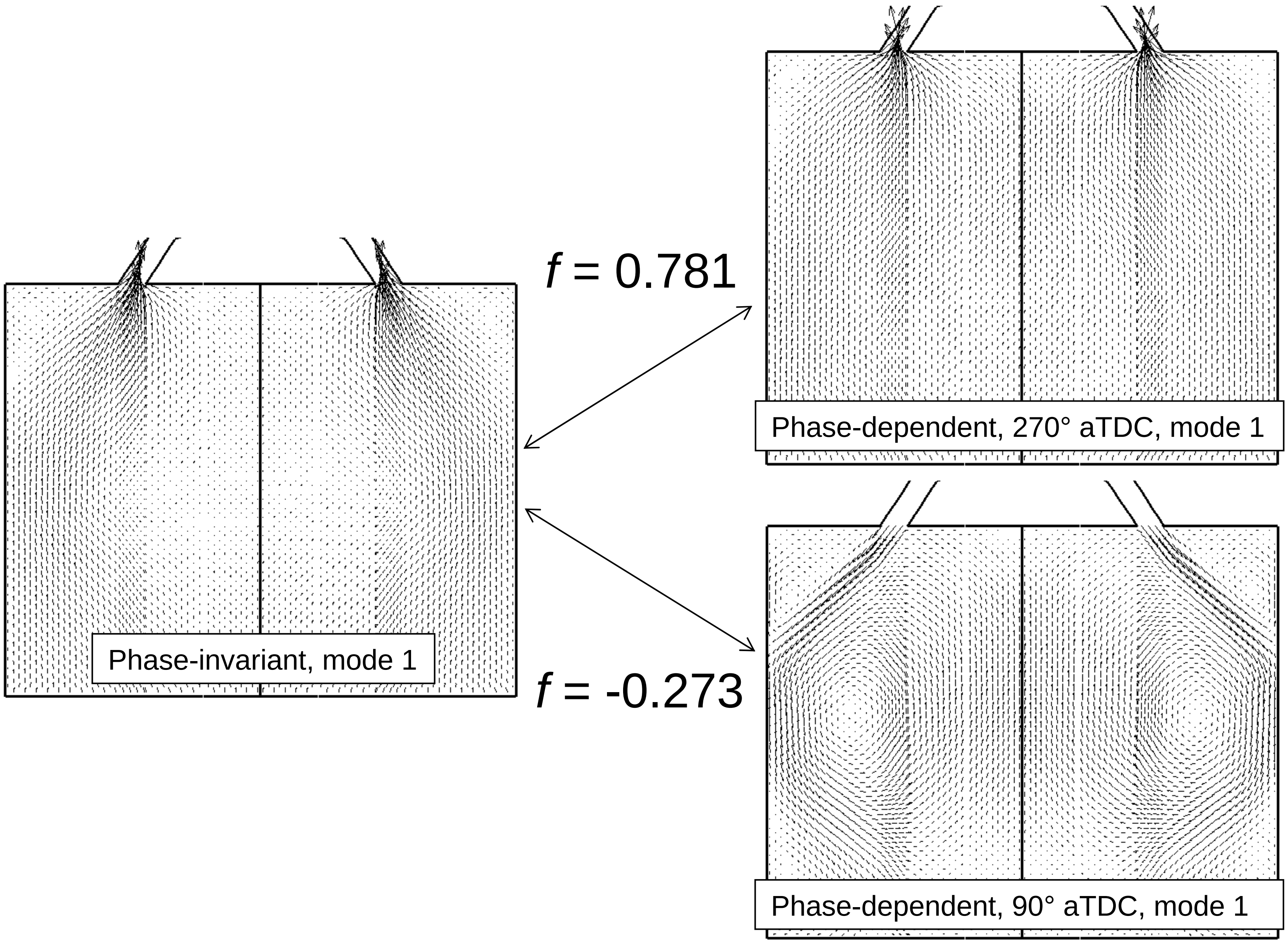
30 cycles used,
variation in number of phases





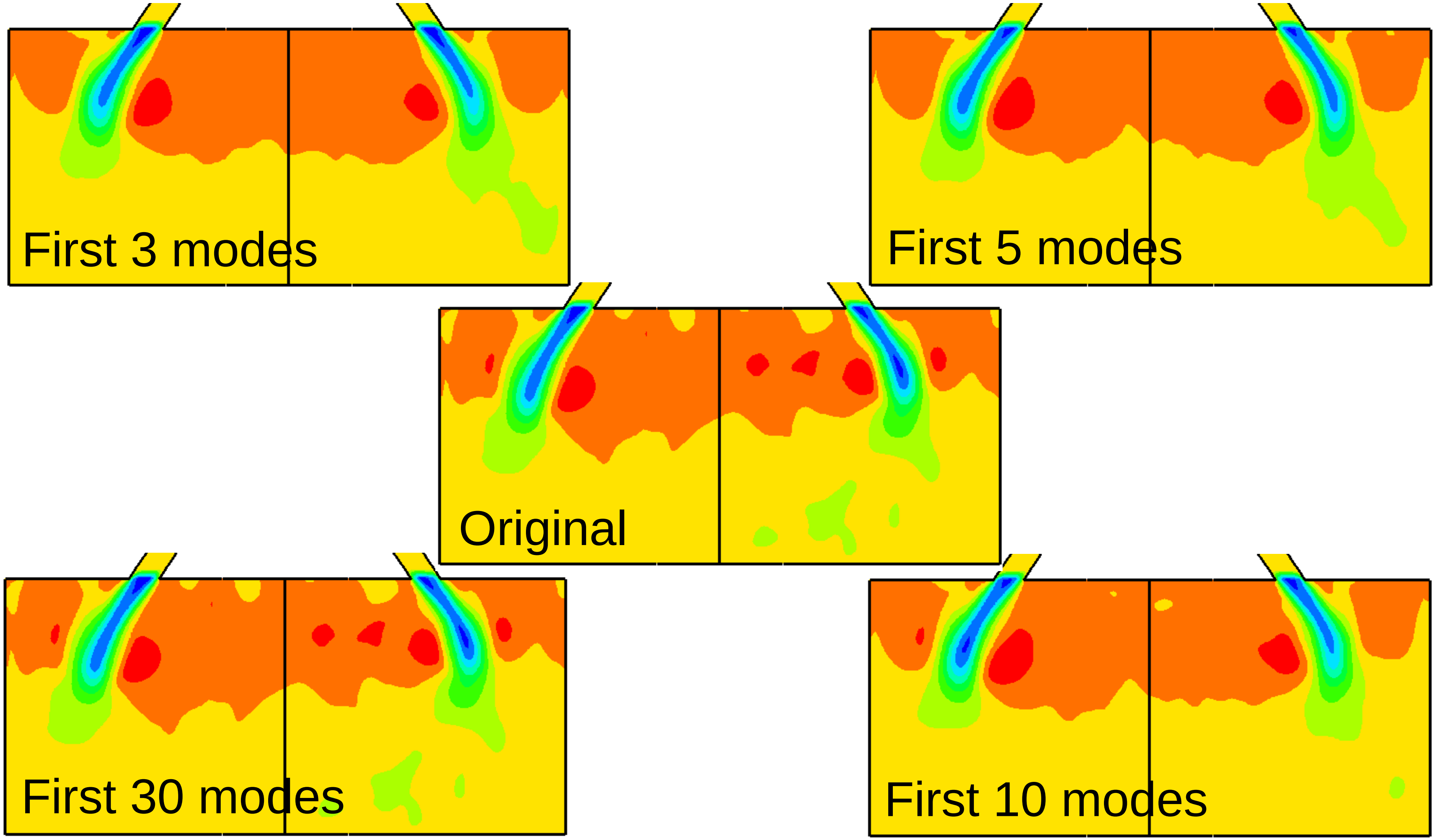
2D and 3D phase-invariant POD, 2D for cutting plane containing cylinder axis, nonswirling case

Phase-invariant POD (cont.)



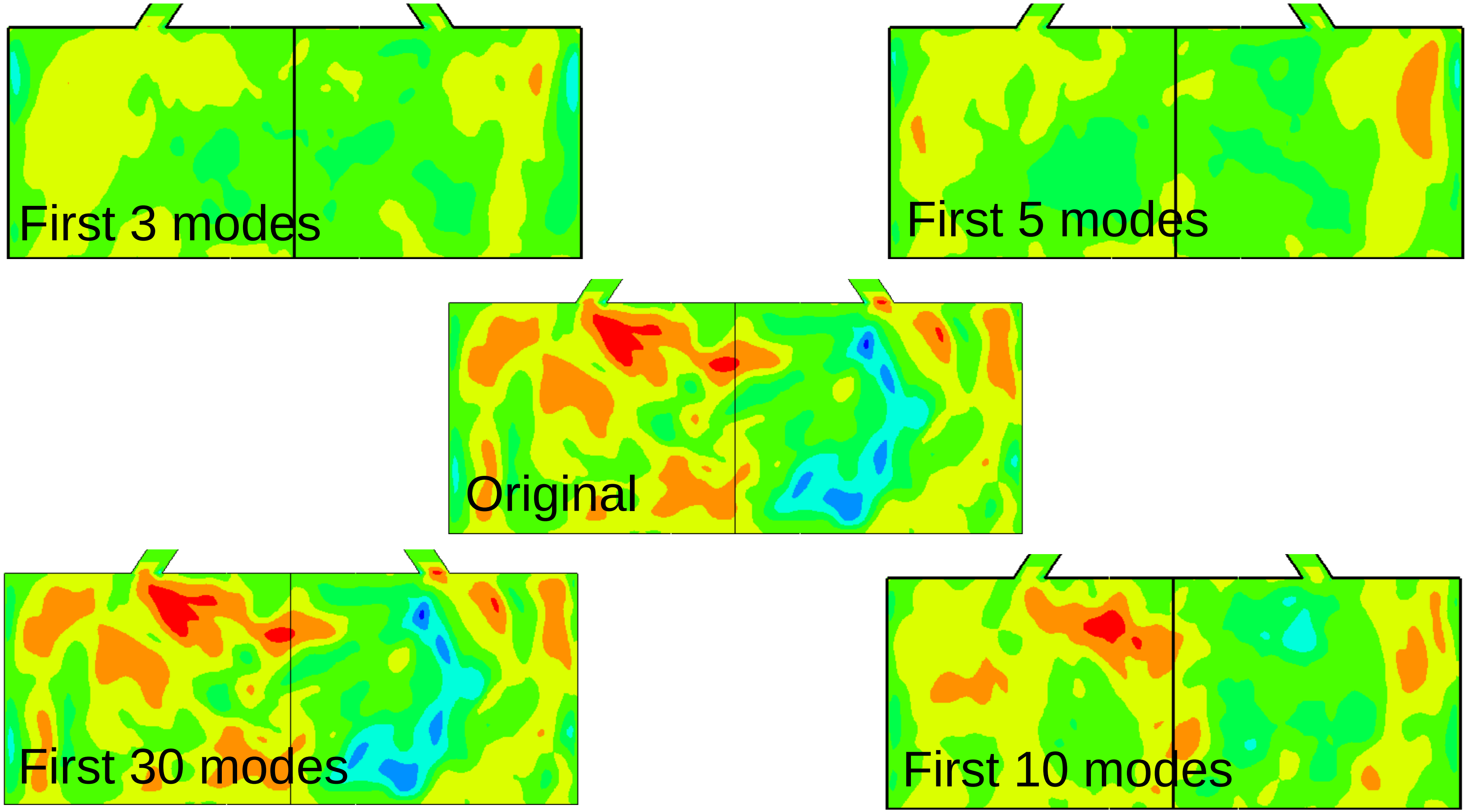
2D POD, cutting plane containing cylinder axis, nonswirling case

The original flow can be reconstructed using phase-dependent or phase-invariant POD modes



2D phase-dependent POD, cutting plane containing cylinder axis, 30° aTDC, nonswirling, cycle 3

Flow reconstruction (cont.)



2D phase-dependent POD, cutting plane containing cylinder axis, TDC, nonswirling, cycle 3

Flow reconstruction (cont.)

	First Mode	First 3 Modes	First 10 Modes	First 30 Modes
TDC	0.454	0.566	0.792	1.000
30° aTDC	0.943	0.970	0.979	1.000
90° aTDC	0.917	0.938	0.962	1.000
BDC	0.692	0.718	0.892	1.000
270° aTDC	0.906	0.911	0.924	1.000
330° aTDC	0.858	0.870	0.943	1.000

$$f \equiv \frac{(\boldsymbol{u}, \boldsymbol{v})}{\|\boldsymbol{u}\| \|\boldsymbol{v}\|}$$

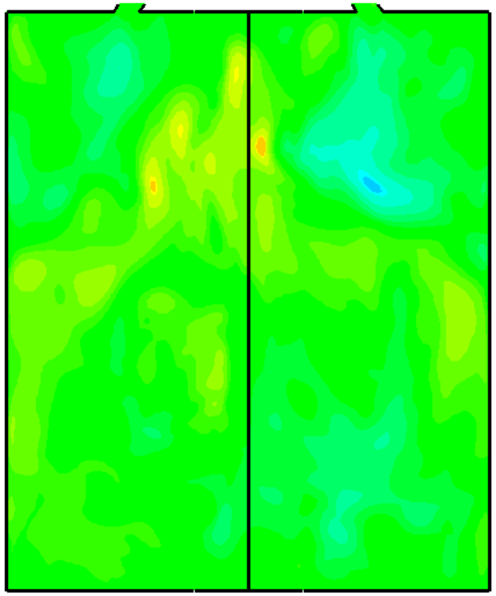
2D phase-dependent POD, cutting plane containing cylinder axis, nonswirling case, cycle 3

Flow reconstruction (cont.)

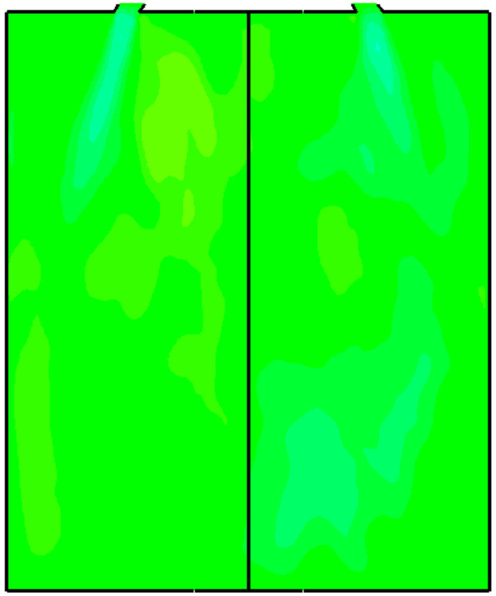
	First 3 Modes	First 10 Modes	First 30 Modes	All 10,800 Modes*
TDC	0.593	0.757	0.971	1.000
30° aTDC	0.754	0.873	0.925	1.000
60° aTDC	0.928	0.937	0.955	1.000
90° aTDC	0.911	0.929	0.943	1.000
120° aTDC	0.897	0.912	0.932	1.000
150° aTDC	0.766	0.801	0.920	1.000
BDC	0.679	0.776	0.874	1.000
210° aTDC	0.621	0.791	0.918	1.000
240° aTDC	0.718	0.812	0.949	1.000
270° aTDC	0.804	0.862	0.943	1.000
300° aTDC	0.816	0.899	0.944	1.000
360° aTDC	0.734	0.889	0.941	1.000

3D phase-invariant POD, nonswirling case, cycle 3

Flow reconstruction (cont.)

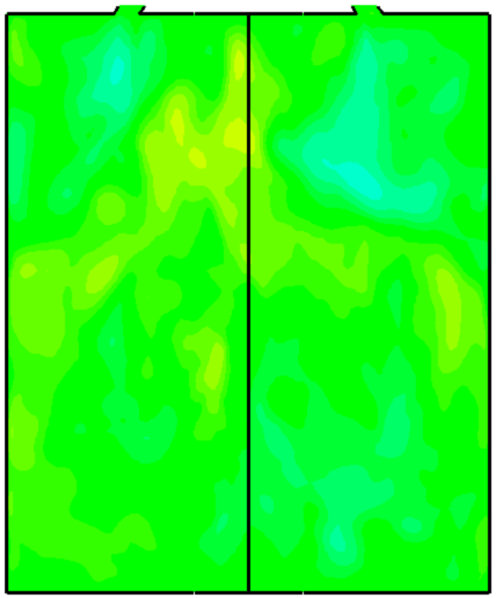


Original

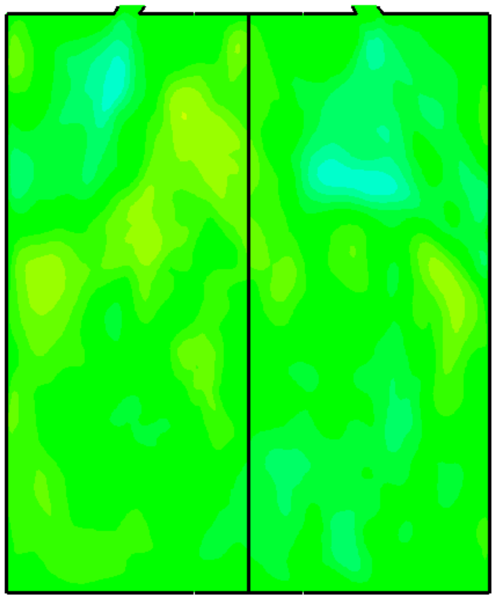


First 3 modes

First 30 modes

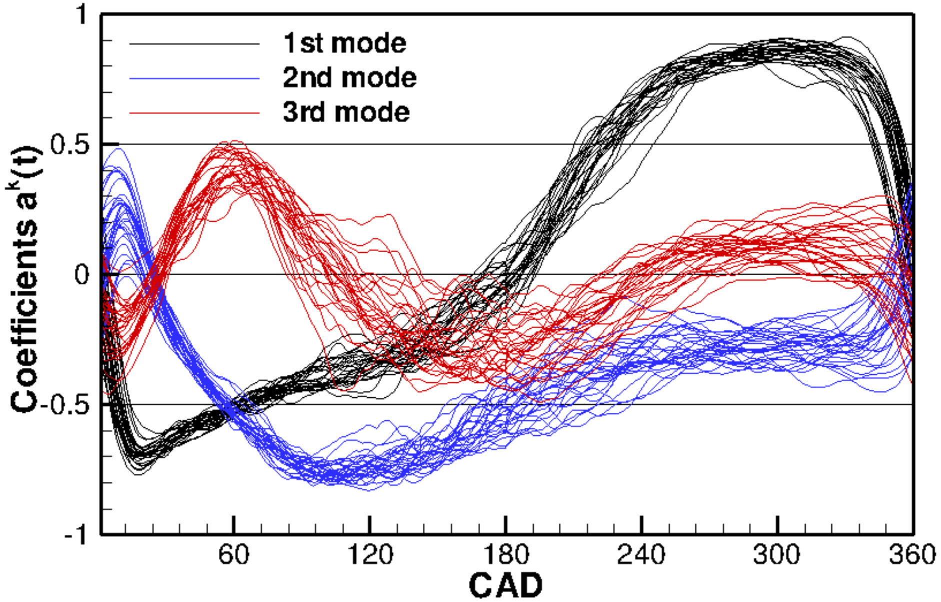


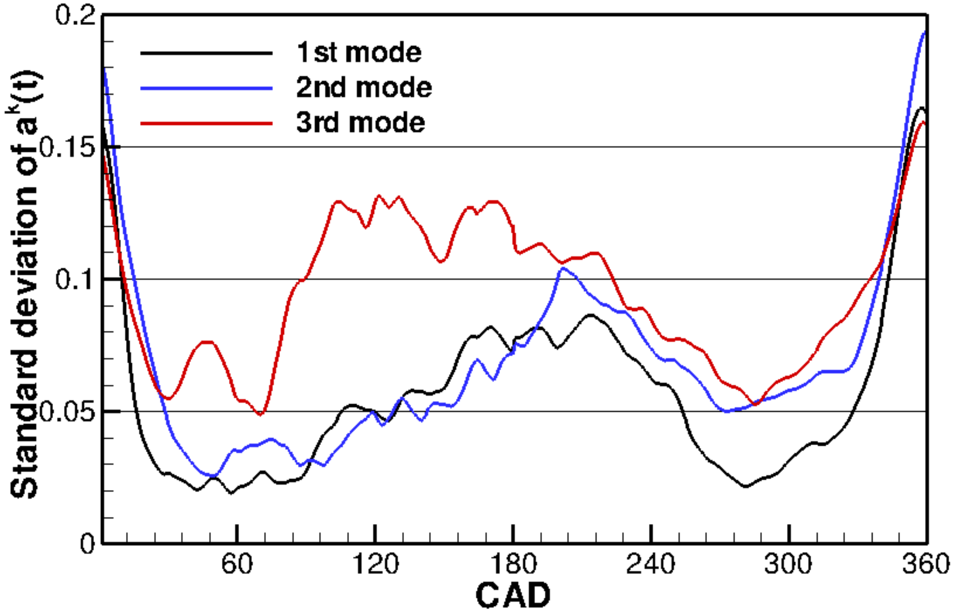
First 10 modes



2D phase-invariant POD, cutting plane containing cylinder axis, nonswirling case, cycle 3

Cycle-to-cycle variations can be quantified using POD

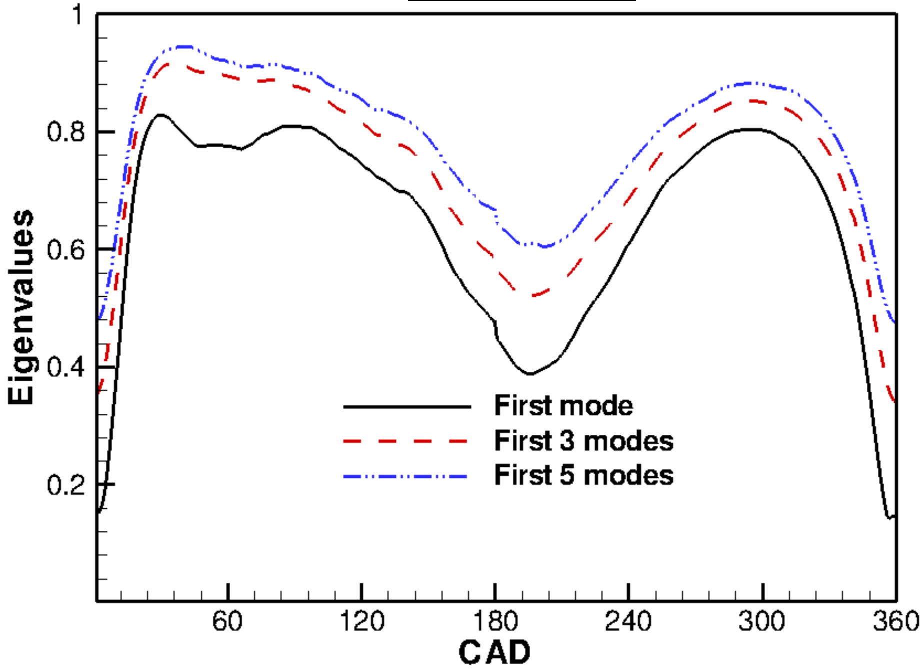




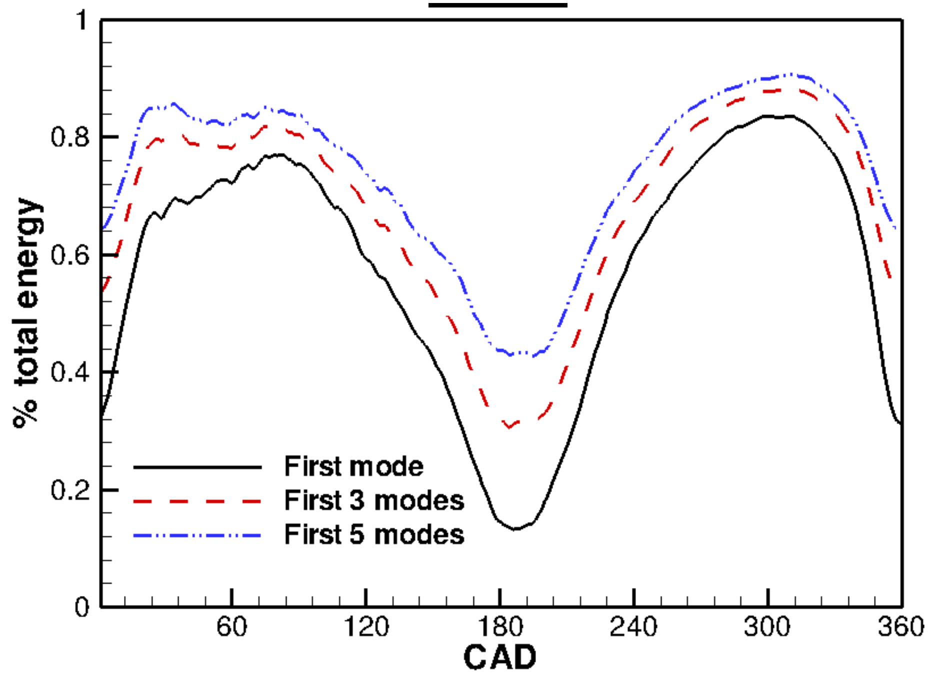
2D phase-invariant POD, cutting plane containing cylinder axis, nonswirling case

Differences can be discerned between flows with versus without swirl

No swirl



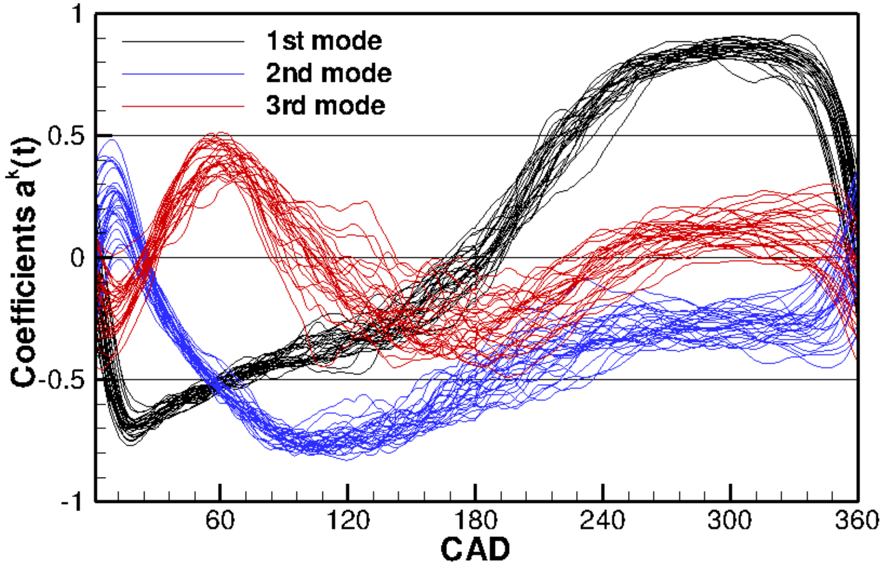
Swirl

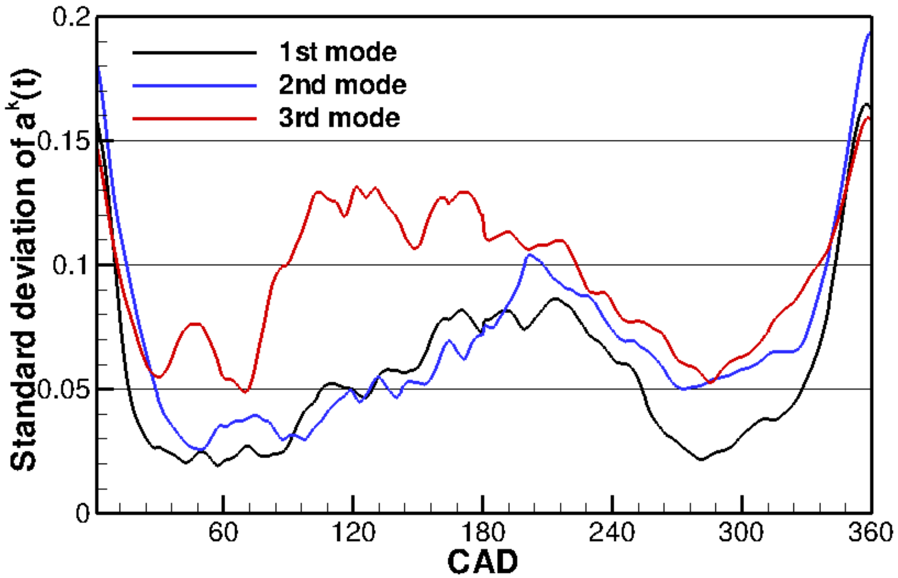


2D phase-dependent POD, cutting plane containing cylinder axis

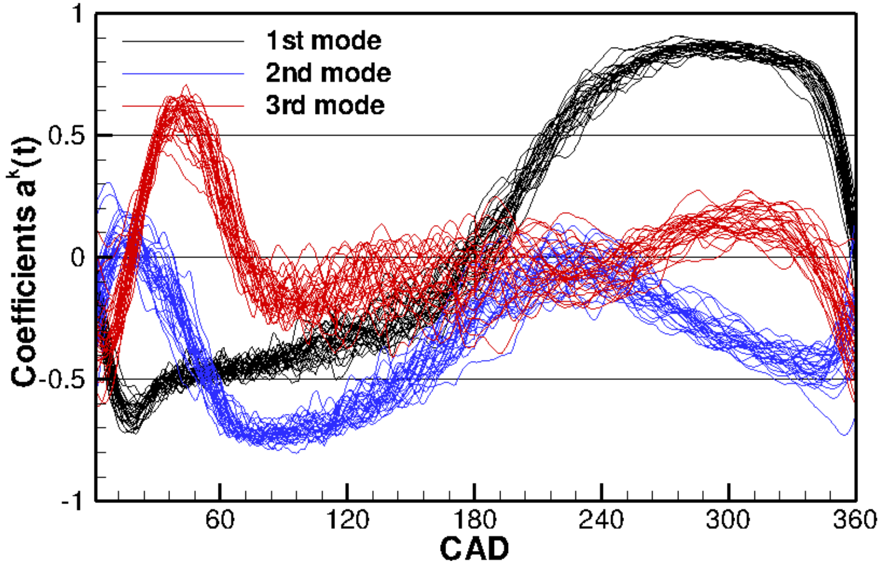
Swirl versus no swirl (cont.)

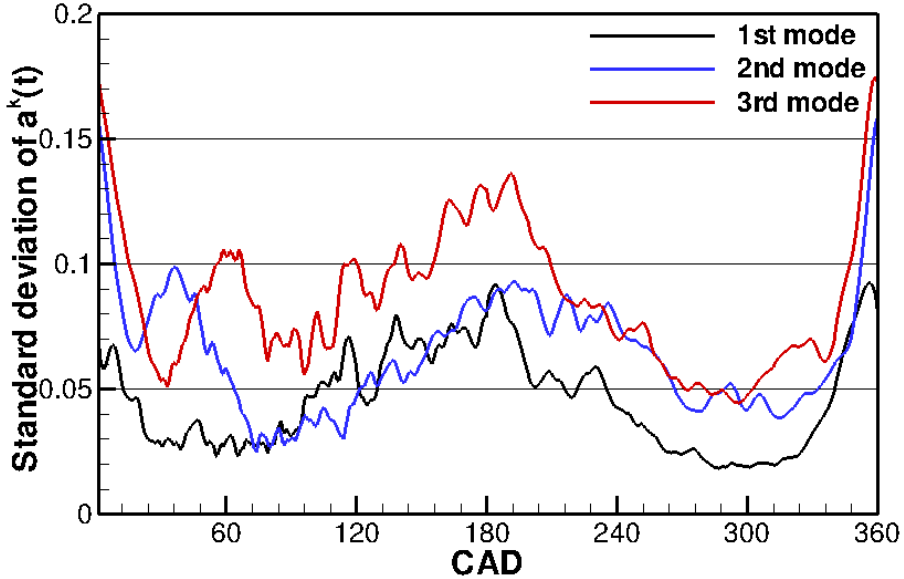
<u>No swirl</u>





<u>Swirl</u>



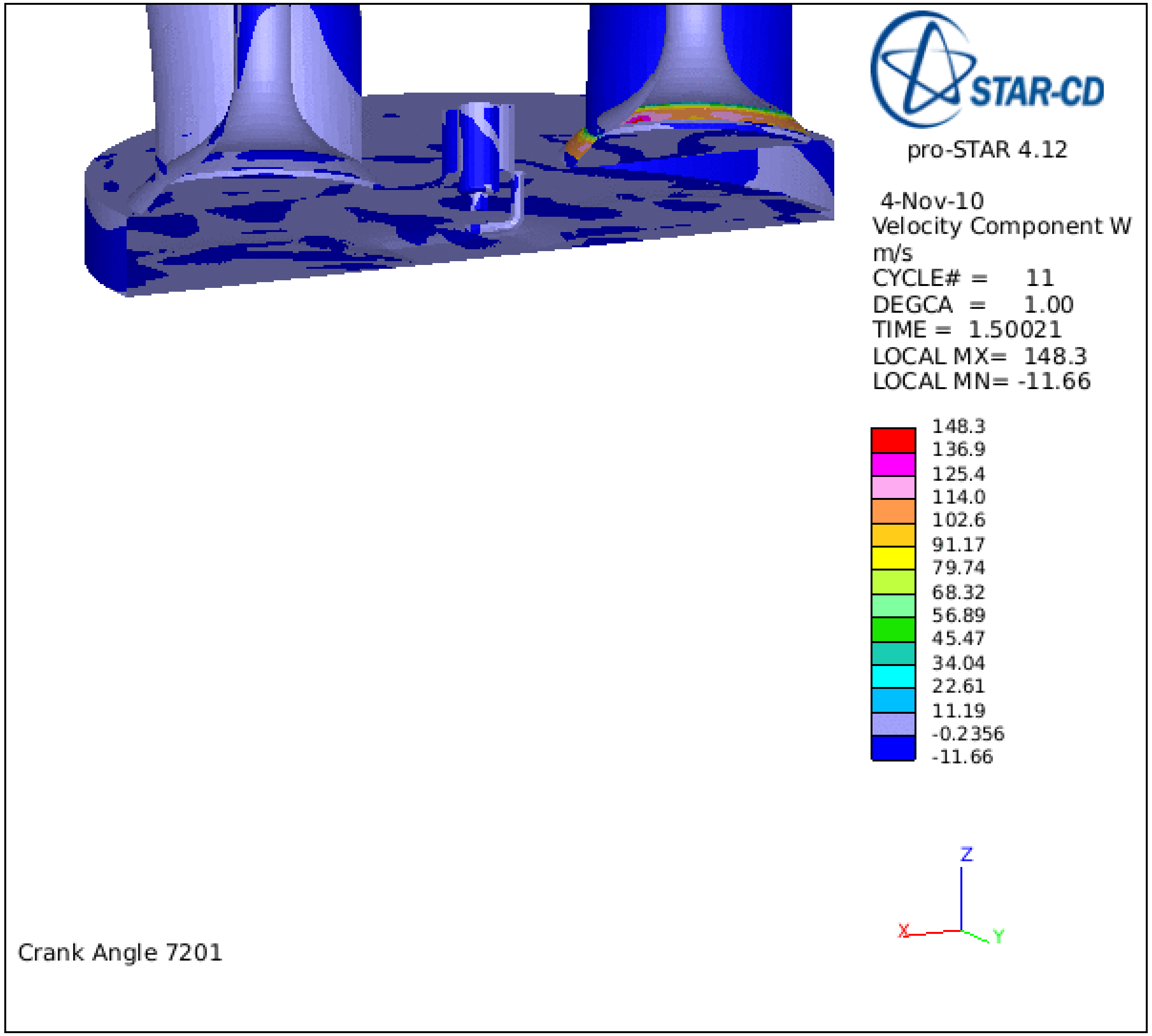


2D phase-invariant POD, cutting plane containing cylinder axis

Summary and conclusions

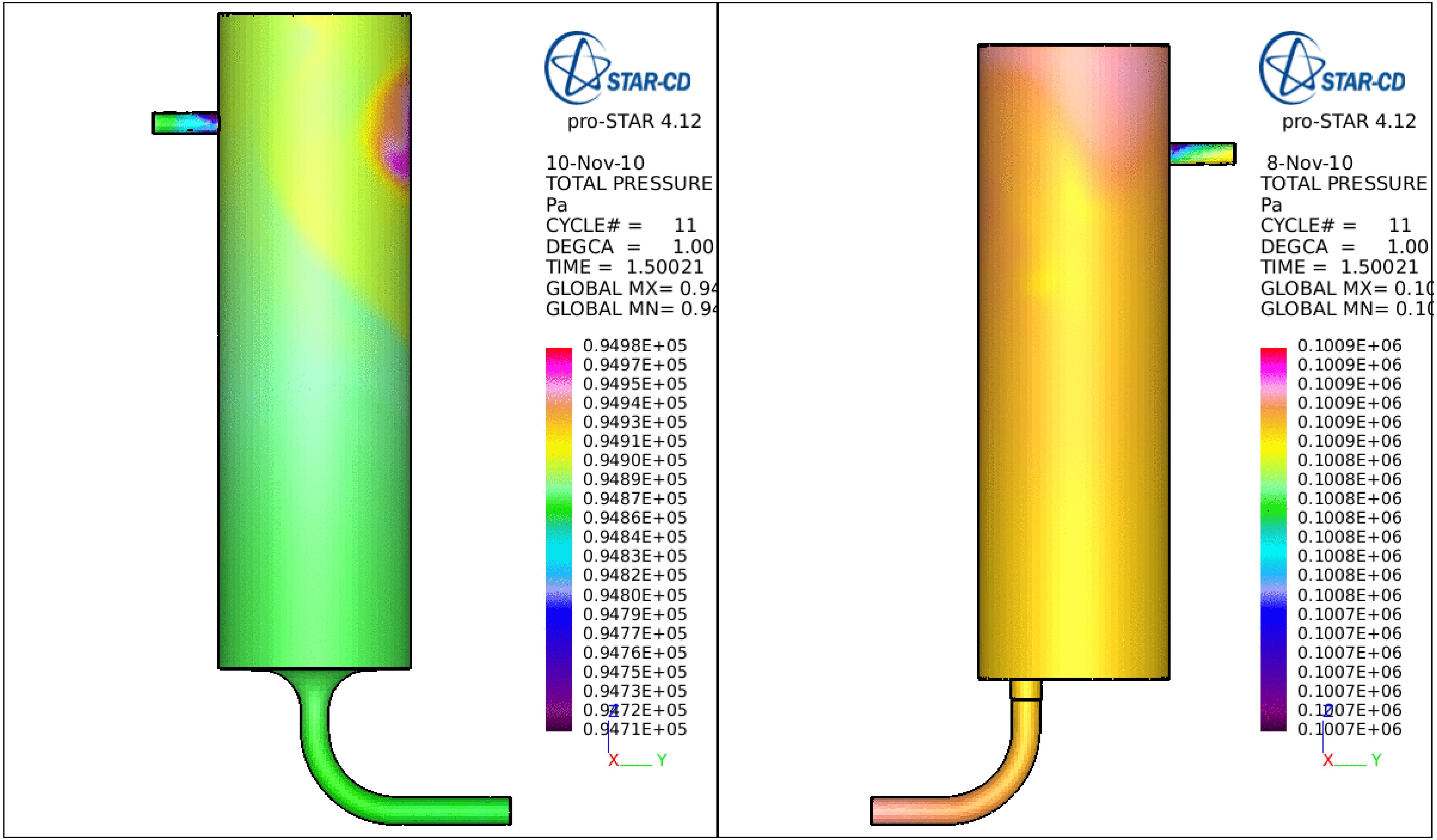
- A systematic and comprehensive study of POD has been performed using datasets obtained from LES for simple engine configurations
- The degree of flow organization varies over the engine cycle
- The first POD mode resembles the ensemble average for well-organized flows
- The number of cycles required for convergence of POD modes varies with the degree of flow organization
- A relatively small number of snapshots per cycle is sufficient for converged POD modes with phase-invariant POD
- Kinetic energy normalization is essential for phase-invariant POD; the influence of the divergence transformation is small
- Complex time-varying in-cylinder flows can be reconstructed using a relatively small number of POD modes
- Cycle-to-cycle variations can be quantified using POD

Simulations are underway for the Transparent Combustion Chamber (TCC) engine



- See Sick et al., A Common Engine Platform for Engine LES Development and Validation, 12:20 PM today

TCC engine (cont.)



International Conference on LES for Internal Combustion Engine Flows

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Rueil-Malmaison, France, 18 - 19 November 2010