Oral presentation | Reduced order models
Reduced order models-I
Mon. Jul 15, 2024 10:45 AM - 12:45 PM Room C

[1-C-02] Large-eddy Simulations and Reduced-Order Modeling for NACA4412 Flow Near The Stall Angle

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Keywords: LES, DMD, ROM, POD

Large-eddy Simulations and Reduced-Order Modeling for NACA4412 Flow Near The Stall Angle

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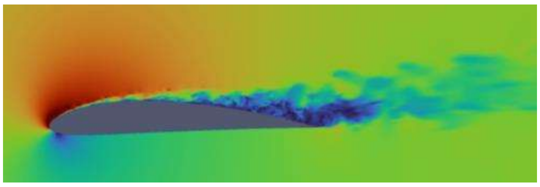

ICCFD12, Kobe, Japan
July 15, 2024

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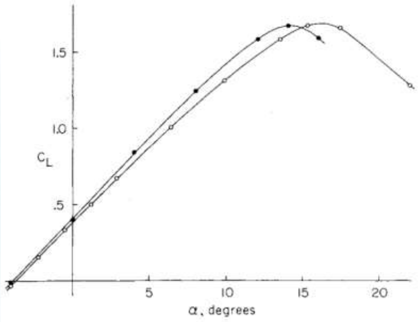
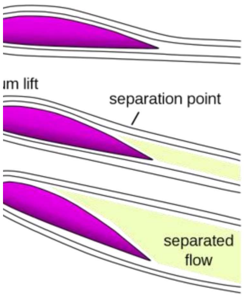
Motivation: Wings at high angle of attack





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Flow Features

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- Vortical Structures
- Separation
- Instability
- Transition
  - K-H Rolls
  - Lambda Vortices

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Large-eddy Simulation

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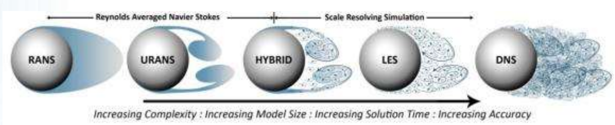
Low-order methods (RANS) cannot resolve unsteady dynamics accurately.

LES is a suitable approach to capture unsteady shock-turbulence interactions.

Simulation of a high α wing flow at high Re is challenging using LES due to several scales involved.



Hart (2016)

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NACA 4412

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Simulations performed near stall angle and realistic flow conditions

Source: Google Images

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Computational Domain

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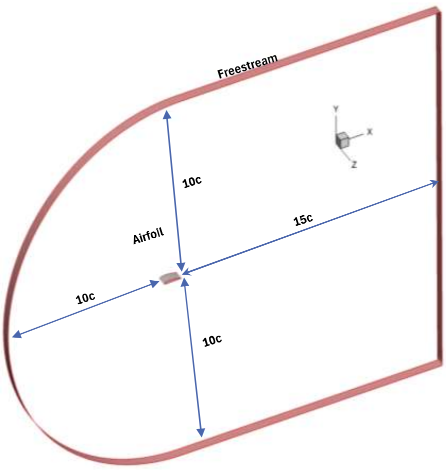

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Computational Mesh

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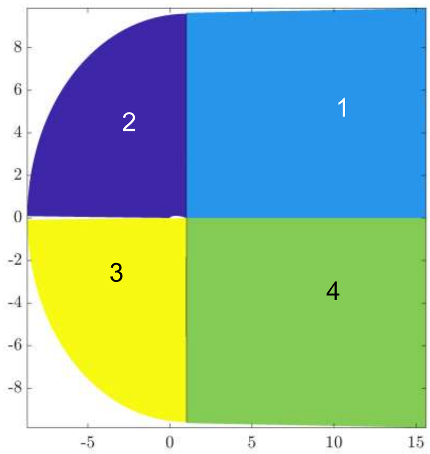

Block	Nx	Ny	Total
1	555	187	103785
2	121	187	22627
3	121	187	22627
4	555	187	103785
Total			252824

Block-structured (C-grid) Mesh

No. of Cells (Coarse) = 0.25 M
No. of Cells (Fine) ~ 1 M

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Computational Mesh

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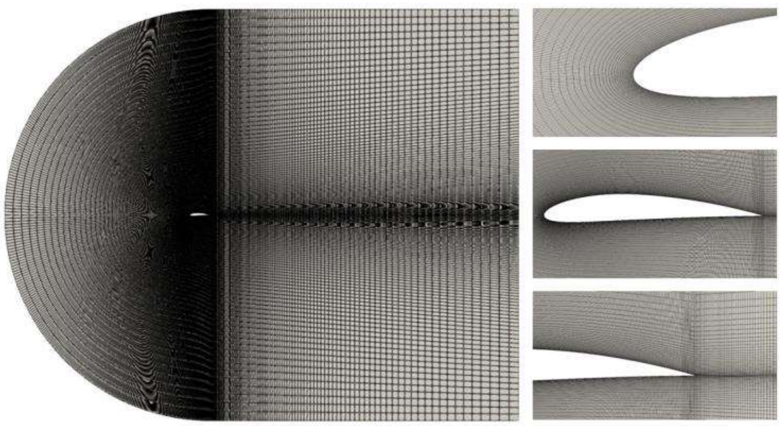

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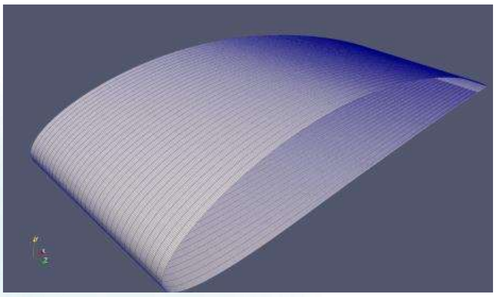
Computational Mesh (3D)



Spanwise BC = Symmetry

Block	Nx	Ny	Nz
1	555	187	32
2	121	187	32
3	121	187	32
4	555	187	32
Total			8090368

Block-structured (C-grid) Mesh

No. of Cells (Coarse) = 8M
No. of Cells (Fine) ~ 24 M (Nz=96)

Solver Setup

- RANS (2D)
  - simpleFOAM
  - Steady-state solver
  - $k-\omega$ SST model
  - Time scheme: First Order (Euler)

- URANS (2D)
  - rhoPimpleFOAM
  - Transient solver
  - $k-\omega$ SST model
  - Time scheme: First Order

- LES (3D)
  - k – equation
  - rhoPimpleFOAM
  - k-equation model
  - Time scheme: Second-order (Backward)

All simulations performed using OpenFOAM-v2212

Dynamical k-equation Model

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$$\frac{\partial k_{SGS}}{\partial t} + \frac{\partial u_i k_{SGS}}{\partial x_i} = 2\nu_{SGS}|\bar{D}_{ij}|^2 - C_e \frac{k_{SGS}^{3/2}}{\Delta} + \frac{\partial}{\partial x_i}\left(\nu_{SGS}\frac{\partial k_{SGS}}{\partial x_i}\right) + \nu \frac{\partial^2 k_{SGS}}{\partial x_i \partial x_i}$$

$\nu_{SGS} = C_k \Delta \sqrt{k_{SGS}}$ represents the SGS kinematic viscosity,

$C_e = 1.048, C_k = 0.094$ are model constants,

$\bar{D}_{ij}$ denotes the filtered strain rate tensor.

- Instead of assuming local equilibrium (production=dissipation), this model solves a transport equation for k
- Improves performance in complex flow situations with non-equilibrium turbulence by accounting for the effects of production, dissipation, and diffusion over time
- Unconditionally stable also in complex geometries without any homogeneous directions

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Flow parameters

- Re = 1.5 x 10^6
- Ma = 0.07
- α = 14°

Boundary Conditions

- Velocity
  1. Freestream – freestreamVelocity
  2. Airfoil – No Slip
- Pressure
  1. Freestream – freestreamPressure
  2. Airfoil – ZeroGradient

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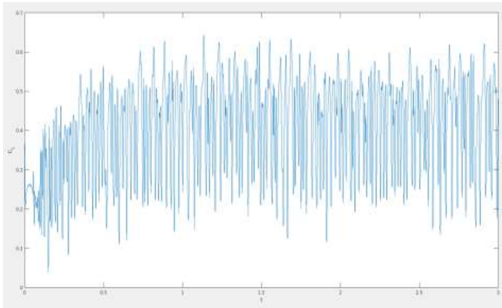
Validation at low angle of attack

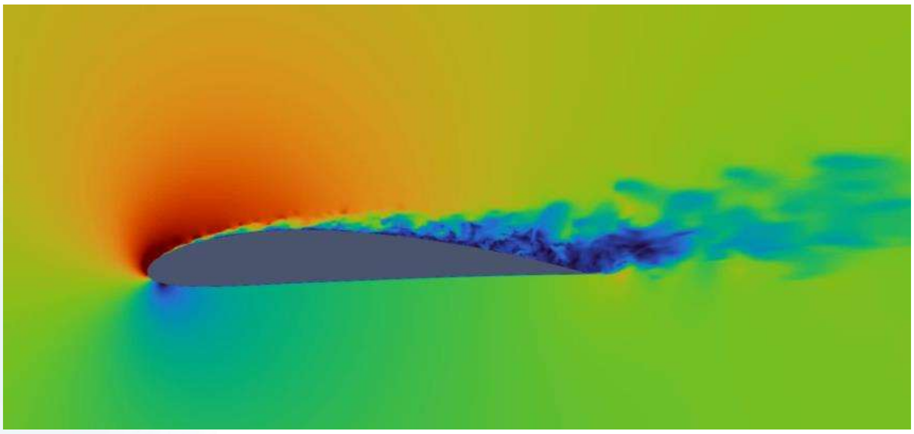
- Angle of Attack = 0°
- Solver = rhoPimpleFoam
- Δt = 2 * 10^{-5} seconds



C_L (Exptl)	C_L (Simulation)
0.415	0.404

2.) Coles, Donald, and Alan J. Wadcock. "Flying-hot-wire study of flow past an NACA 4412 airfoil at maximum lift." *AIAA Journal* 17.4 (1979): 321-329.

LES predictions



LES predictions

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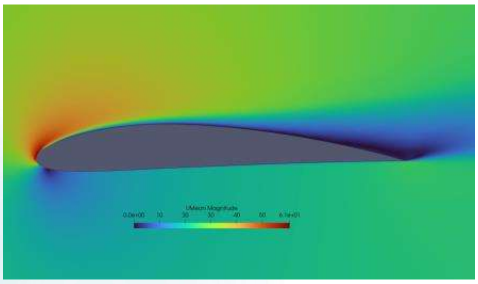

Figure. U_{mean} flood contour around the airfoil

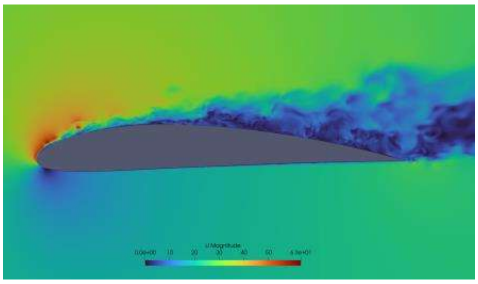

Figure. Flood contour showing $U_{Instantaneous}$

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Mean Flow (LES)

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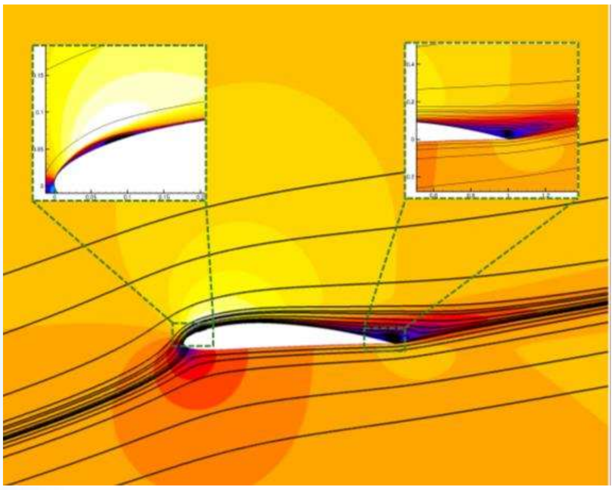

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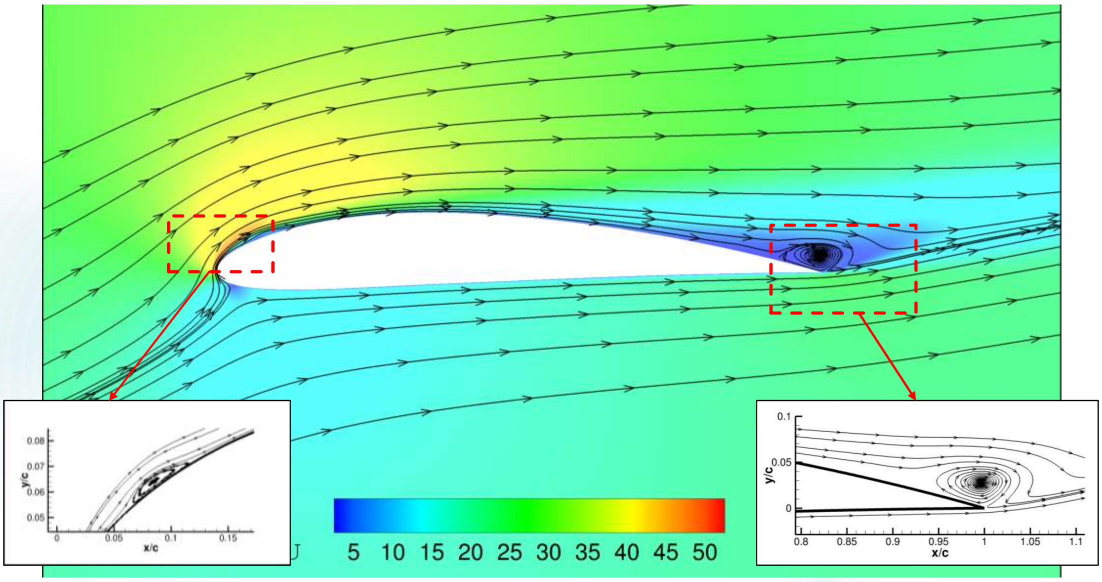

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Grid Convergence

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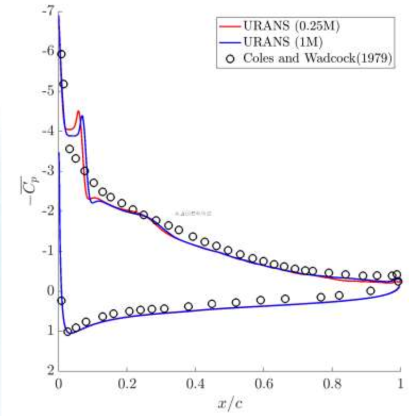

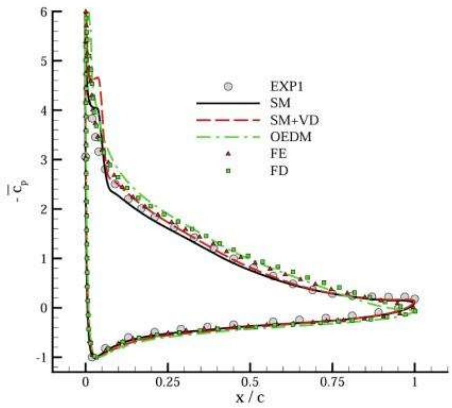

Schmidt, Franke & Thiele (2001) - $\alpha = 12^0$

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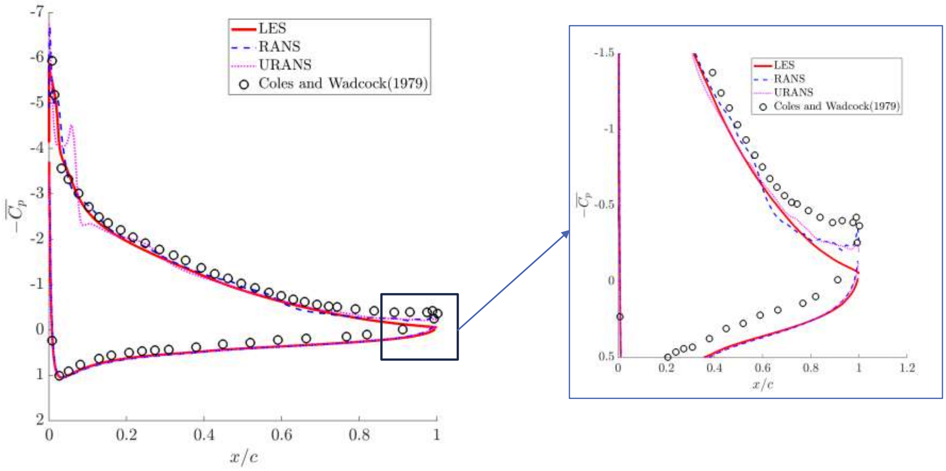
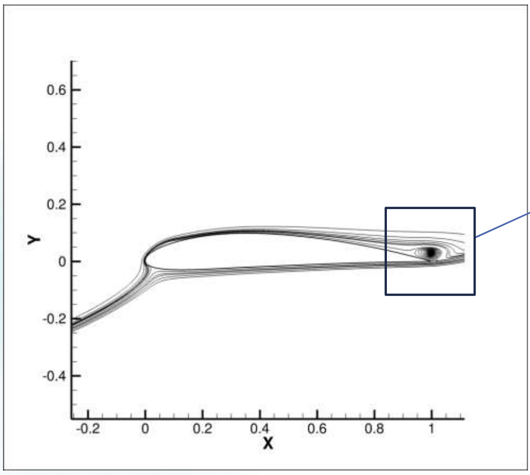
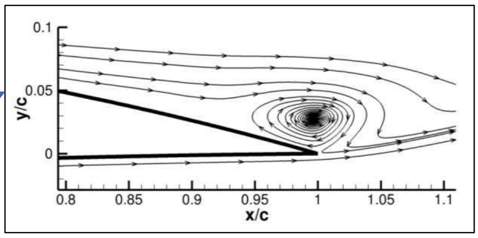
Mean Flow Features

Pressure Prediction



LES

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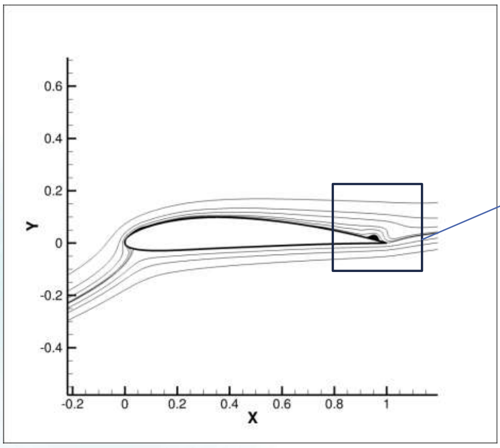
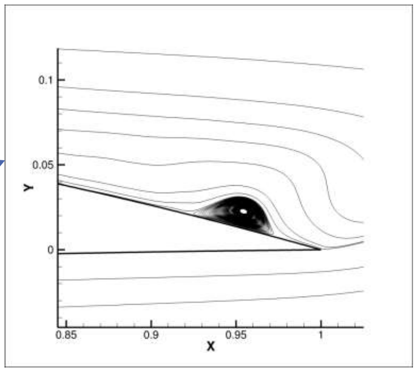
URANS

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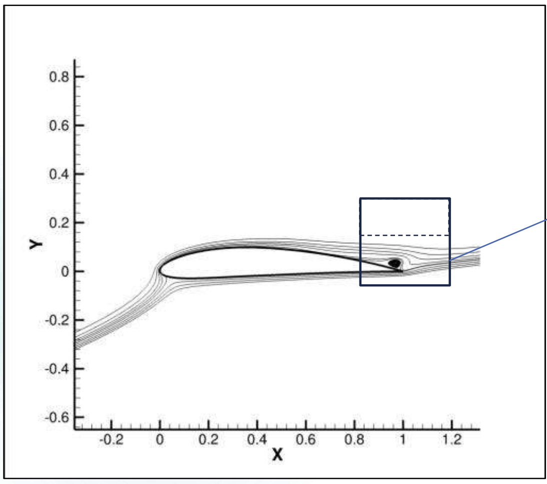
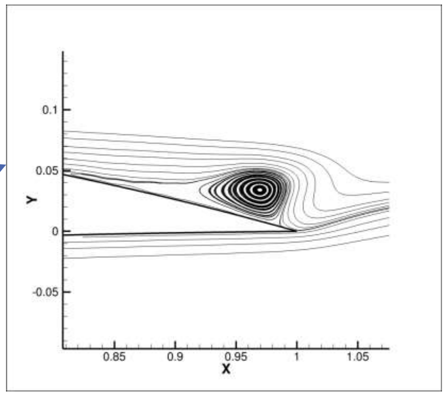
RANS





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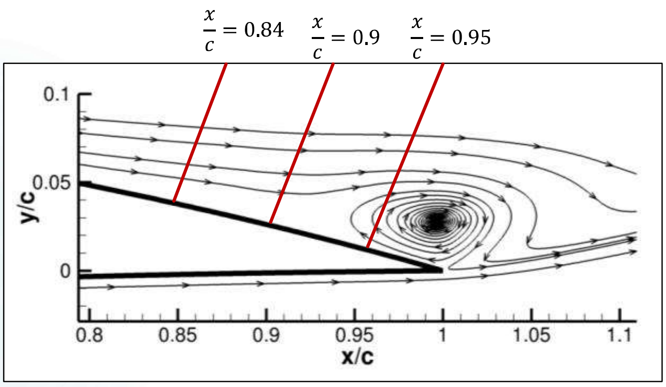
Velocity Profiles



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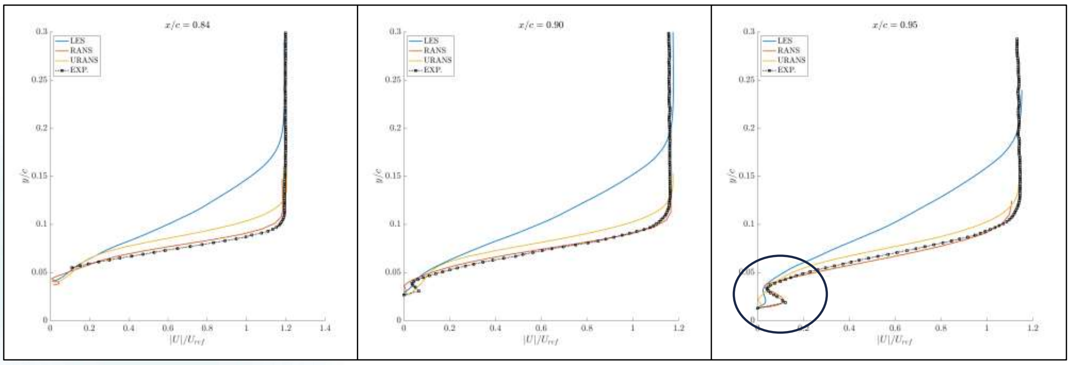
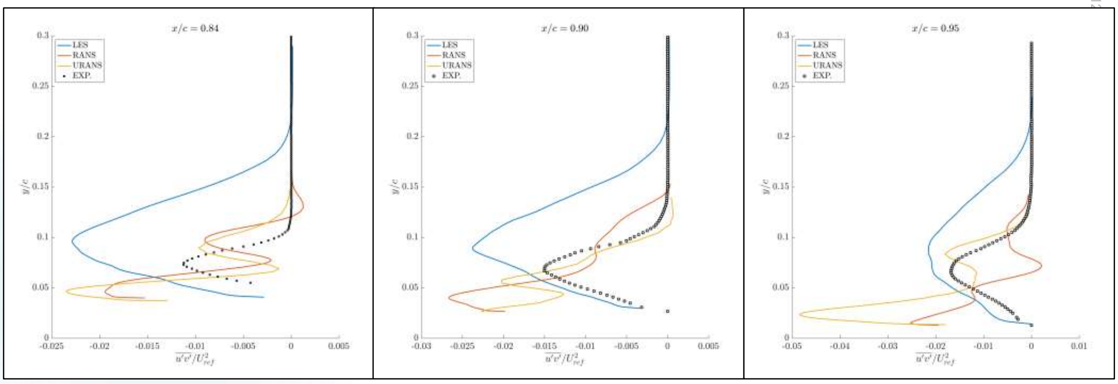
Velocity Profiles



Experimentally measured separation point at $\frac{x}{c} \approx 0.86$

Exp.: Coles, Donald, and Alan J. Wadcock. "Flying-hot-wire study of flow past an NACA 4412 airfoil at maximum lift." *AIAA Journal* 17.4 (1979): 321-329.

Reynolds Stress Comparisons



Flow Transition

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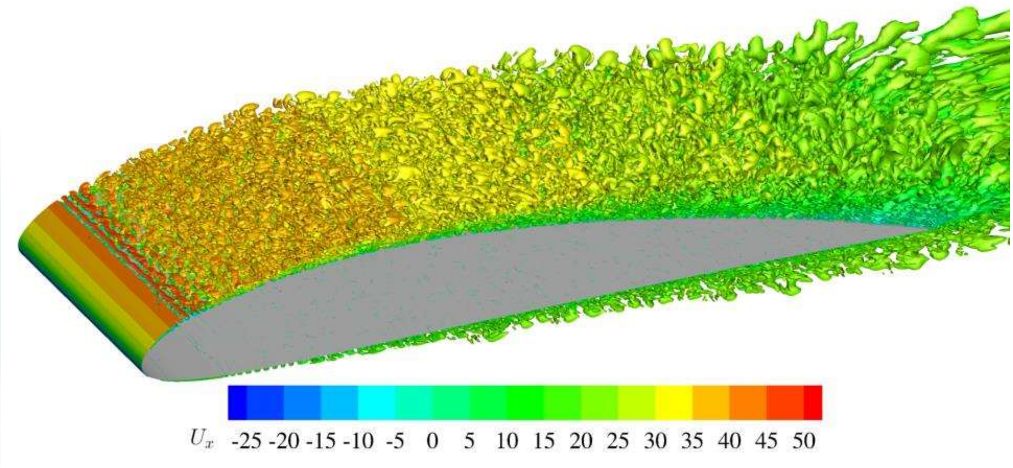
Q – Iso-Surfaces



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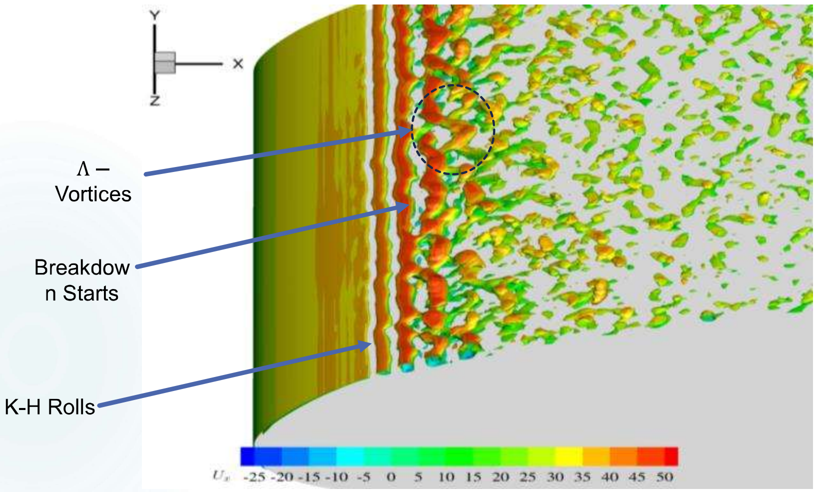
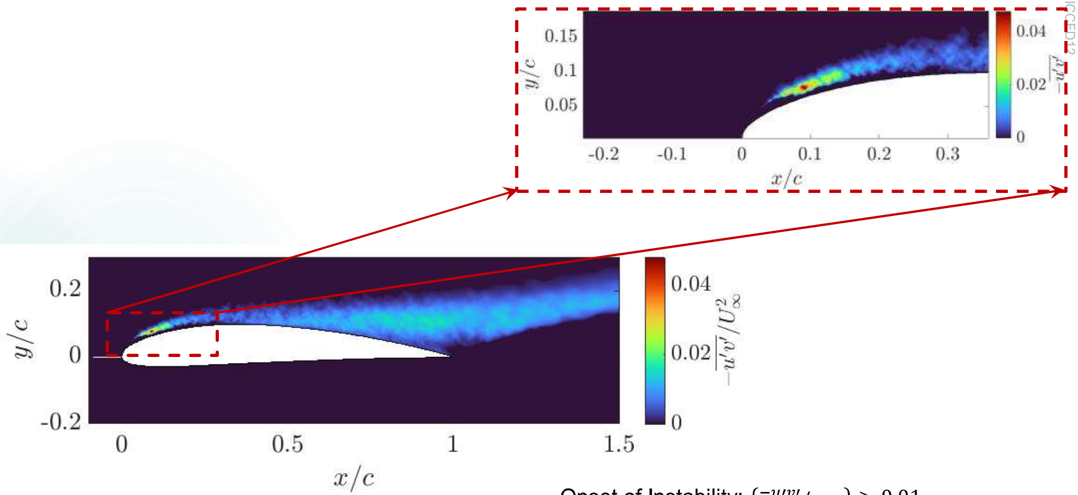
K-H Roll Breakdown



Flow Transition



Onset of Instability: $\left\{ {}^{-u'v'}/_{U^2_{\{\infty\}}} \right\} > 0.01$

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Unsteady Flow Analysis

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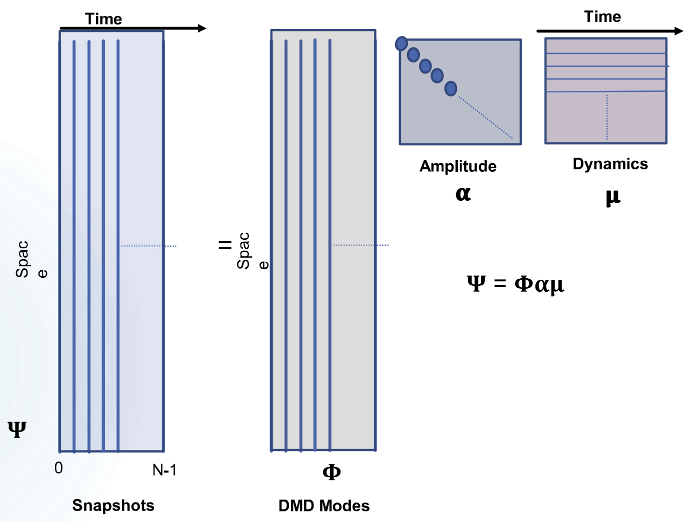
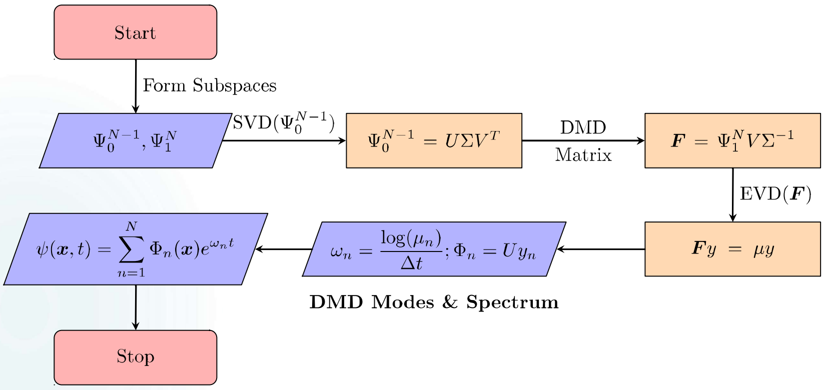
Dynamic Mode Decomposition

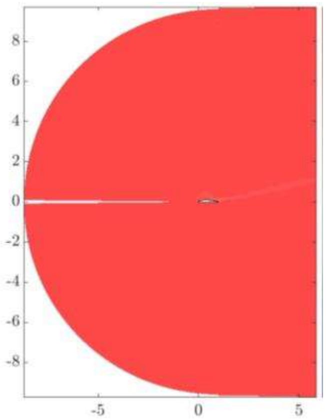


DMD Algorithm



Dynamic Mode Decomposition (DMD)

- DMD performed on the midplane of LES snapshots
- Velocity (u & v) variables are chosen for the analysis
- Snapshots are taken after discarding initial transient datasets
- DMD convergence is obtained by varying number of snapshots
- DMD performed on a reduced domain



DMD/POD Domain

DMD – Selection of Snapshots

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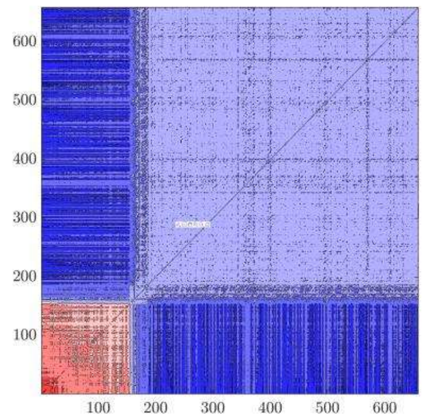
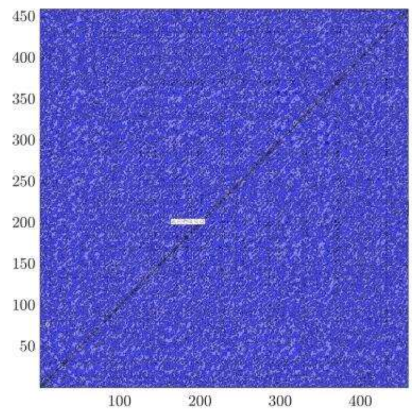


Initial



After removing Transients

Dynamic Mode Decomposition (DMD)

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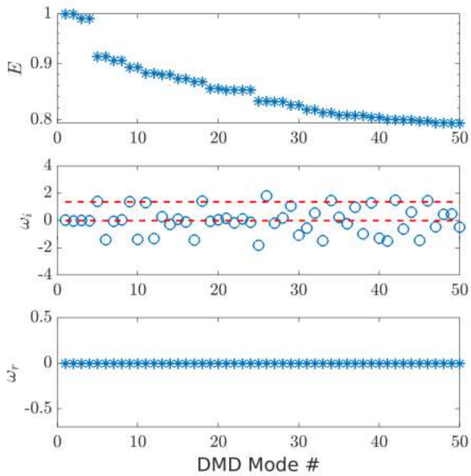
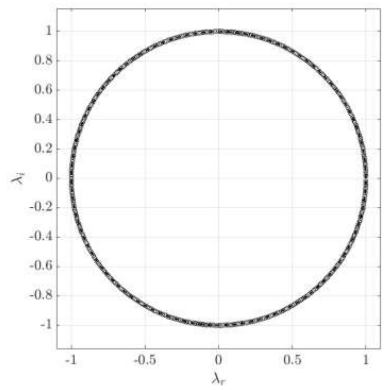
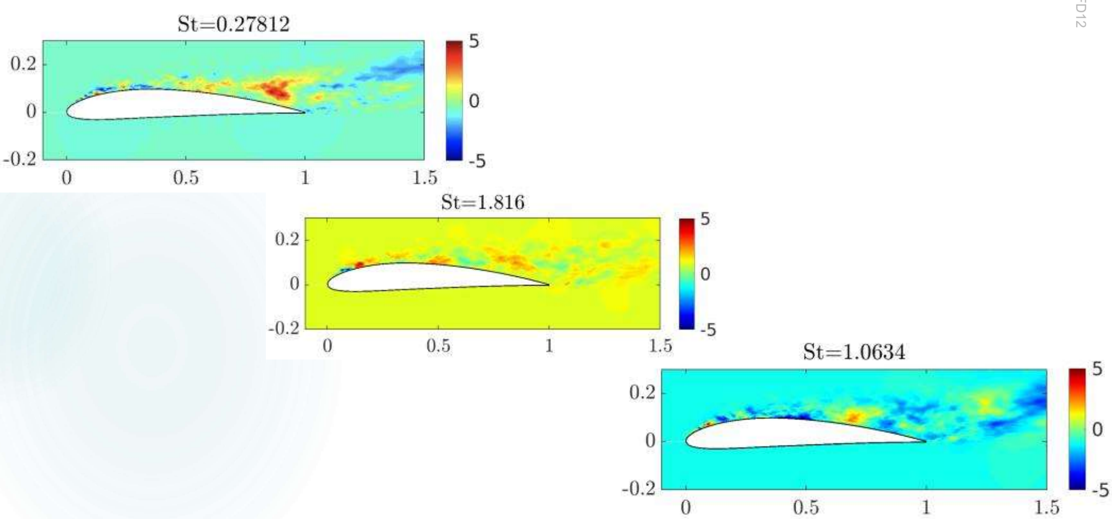




DMD Modes



Proper Orthogonal Decomposition (POD)

Method of Snapshots

$$\mathbf{X} = \begin{bmatrix} | & | & & | \\ u_1 & u_2 & \cdots & u_N \\ | & | & & | \end{bmatrix}$$

Formation of covariance matrix

$$\mathbf{C} = \frac{1}{N}\mathbf{X}\mathbf{X}^T$$

Eigenvalue Decomposition

$$\mathbf{C}\mathbf{v}_i = \lambda_i \mathbf{v}_i$$

Proper Orthogonal Decomposition (POD)

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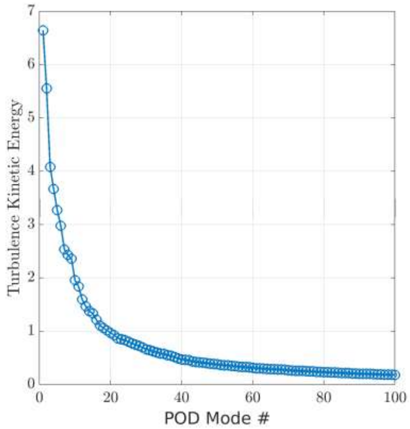

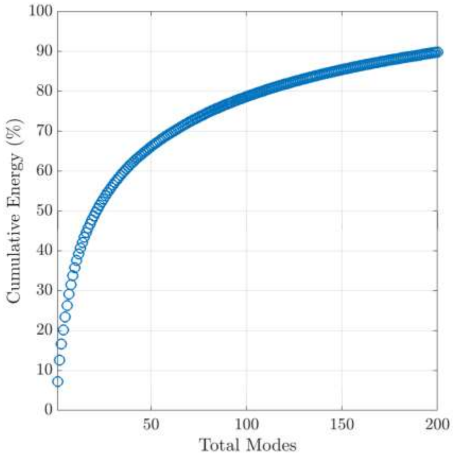

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Proper Orthogonal Decomposition (POD)

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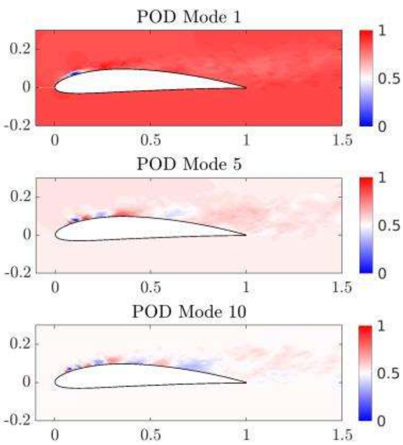

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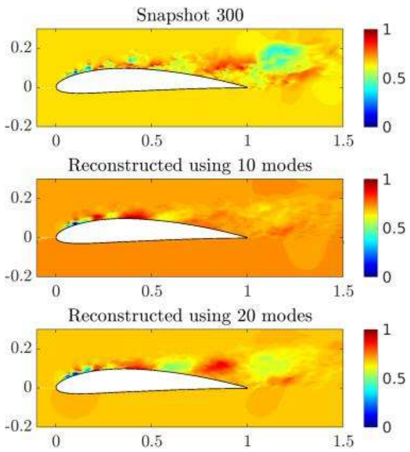
Attempt to ROM

Reconstruction using POD modes

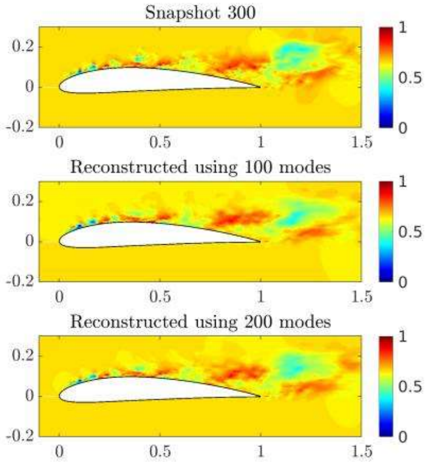
10 Modes: About 35% of TKE

20 Modes: About 48% of TKE



100 Modes: About 78% of TKE

200 Modes: About 90% of TKE



Conclusions

RANS, URANS and LES are performed on NACA4412 wing at 14^0 angle of attack

LES with dynamical k –equation predicts the overall profile well except at the trailing edge, where a smaller separation bubble is predicted

Finer flow structures reveals transition-to-turbulence via K-H instability on the suction side $\frac{x}{c} = 0.05$. However, the transition zone is small due to high Reynolds number.

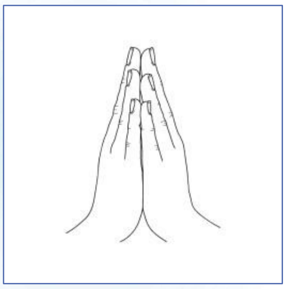
POD analysis suggests that a high-rank system with first 10 modes constituting only 35% of the total kinetic energy.

Reconstruction with about 10 modes shows the K-H modes as well as wake region. However, reproduction of finer structures require more than 200 modes.

Acknowledgments

IIT Kanpur Supercomputing Resources (Param Sanganak)

IIT Kanpur Initiation Grant



Thank you very much!

Contact: rajeshr@iitk.ac.in