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Steady-State Computation of Constant Rotational Rate Dynamic Stability Derivatives

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Outline

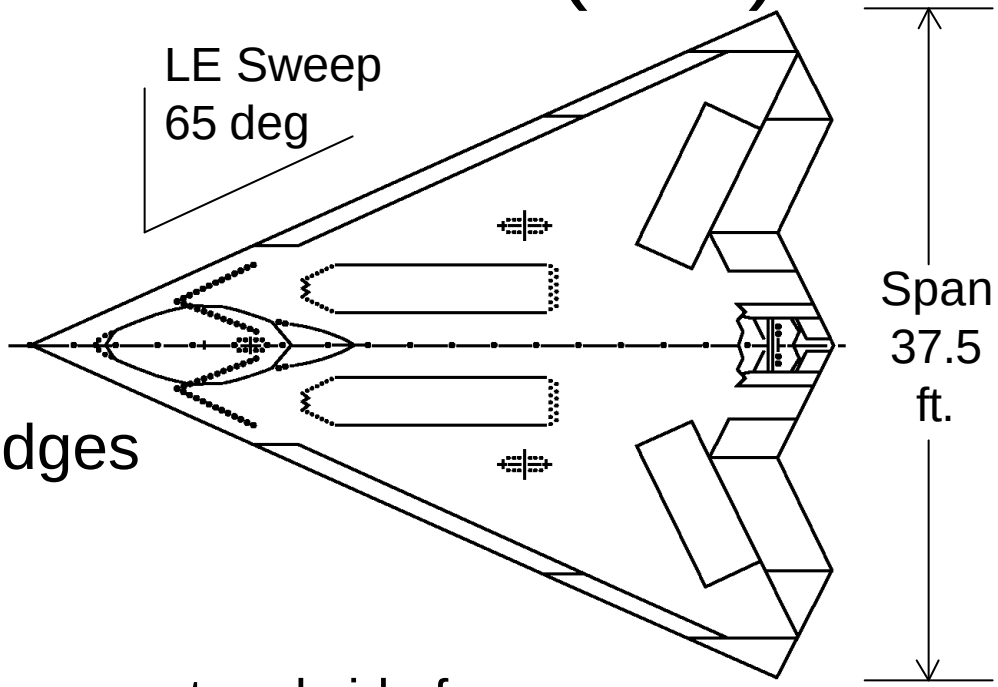
- Motivation and introduction
- Example: ICE configuration
- Turbulent N-S code: CFL3D
- Automatic differentiation process: ADIFOR
- Static computational flow visualization
- Noninertial modifications to CFL3D
  - Body-axis rotational rate derivatives
  - Rotary-balance simulation
  - Computational resources
- Summary and conclusions

http:/fmad-www.larc.nasa.gov/mdob/MDOB/Conference/conf-present.html

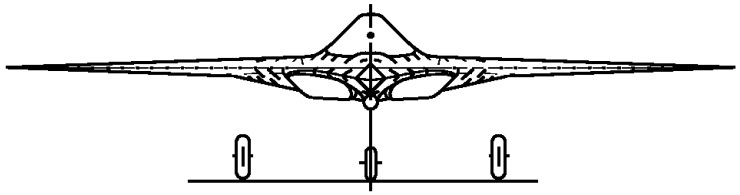
Motivation and Introduction

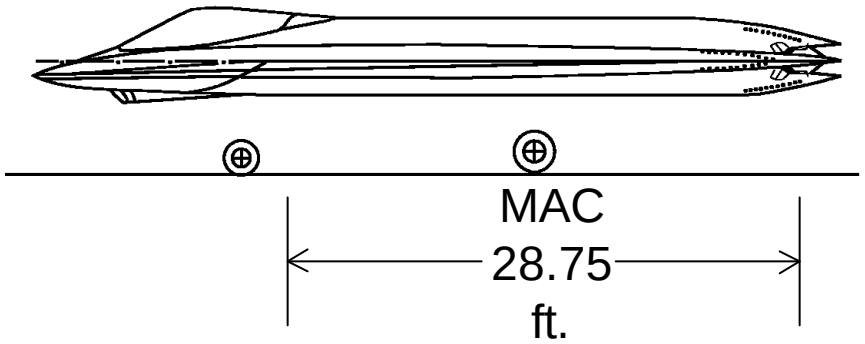
- Need for a high fidelity aerodynamic predictor
  - Reduce dependence on experimental data (S&C)
- Noninertial computational fluid dynamics (CFD)
  - Adding Navier-Stokes (N-S) source term
  - Reduces the overhead of moving grid solutions
  - **Extremely efficient for constant rotational rate motion**
- Automatic differentiation - ADIFOR
  - Exact, no dependencies on finite difference step size
  - Faster than central differencing
  - Static stability (a, b derivatives)
  - **Dynamic stability (*p*, *q*, *r* derivatives)**

Lockheed-Martin Tactical Aircraft Systems Innovative Control Effectors (ICE)

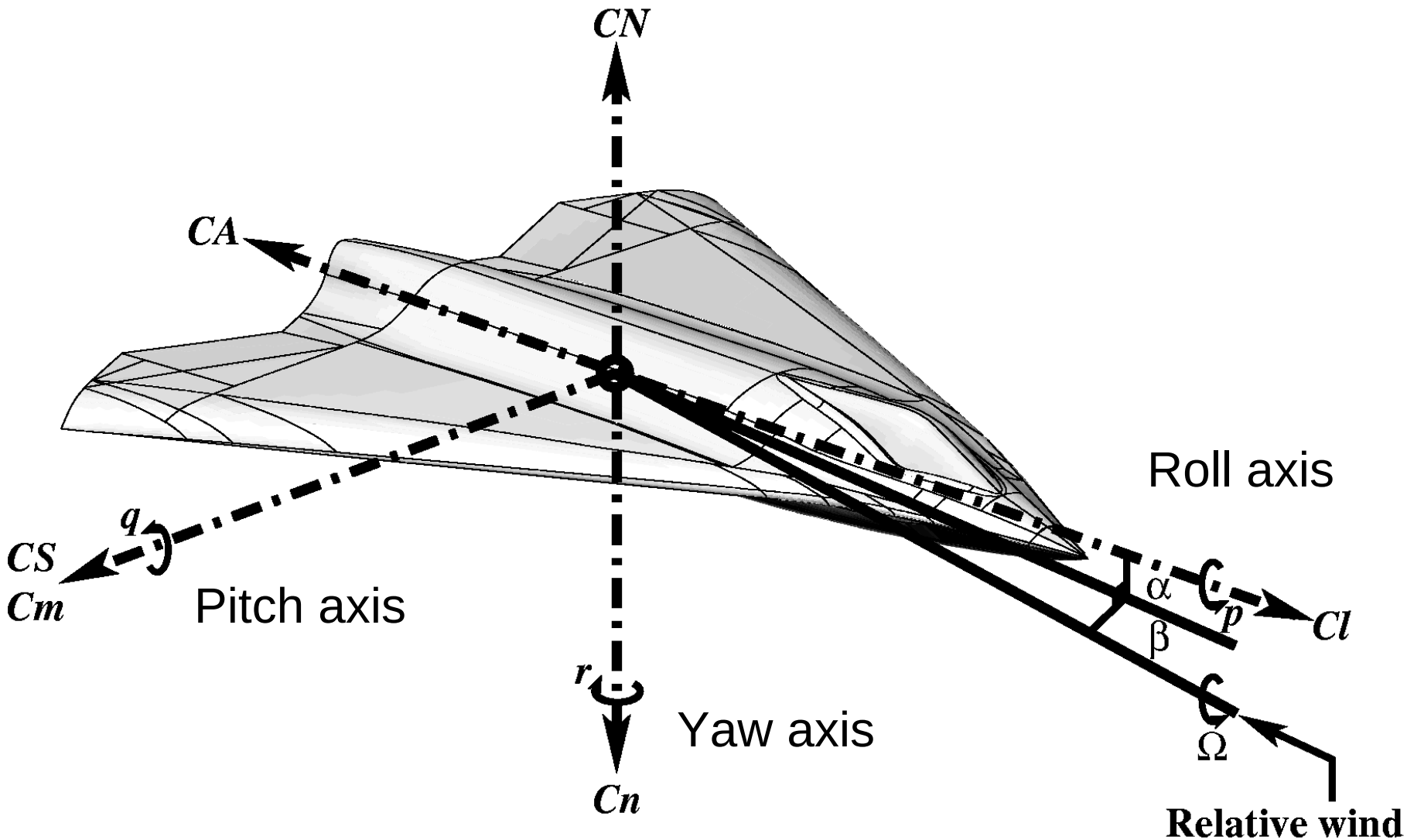


- Concept vehicle
  - Stealth, controllability
  - Highly swept leading edges
    - Vortical flow
  - No vertical surfaces
    - Relatively small yawing moment and side force





ICE Configuration



CFL3D Version 6

- Computational Fluids Laboratory 3-Dimensional
- NASA Langley Research Center
- Thomas, Rumsey, Biedron, …
- Euler and Navier-Stokes (N-S)
- Dynamic memory allocation, Parallel execution
- Steady-state N-S cases presented
  - Spalart-Allmaras (S-A) one equation turbulence model
- ICE grid: 3 million cells, full span
- NASA LaRC HPCCP/CAS Origin 2000™

ADIFOR
(Automatic Differentiation of FORTRAN)

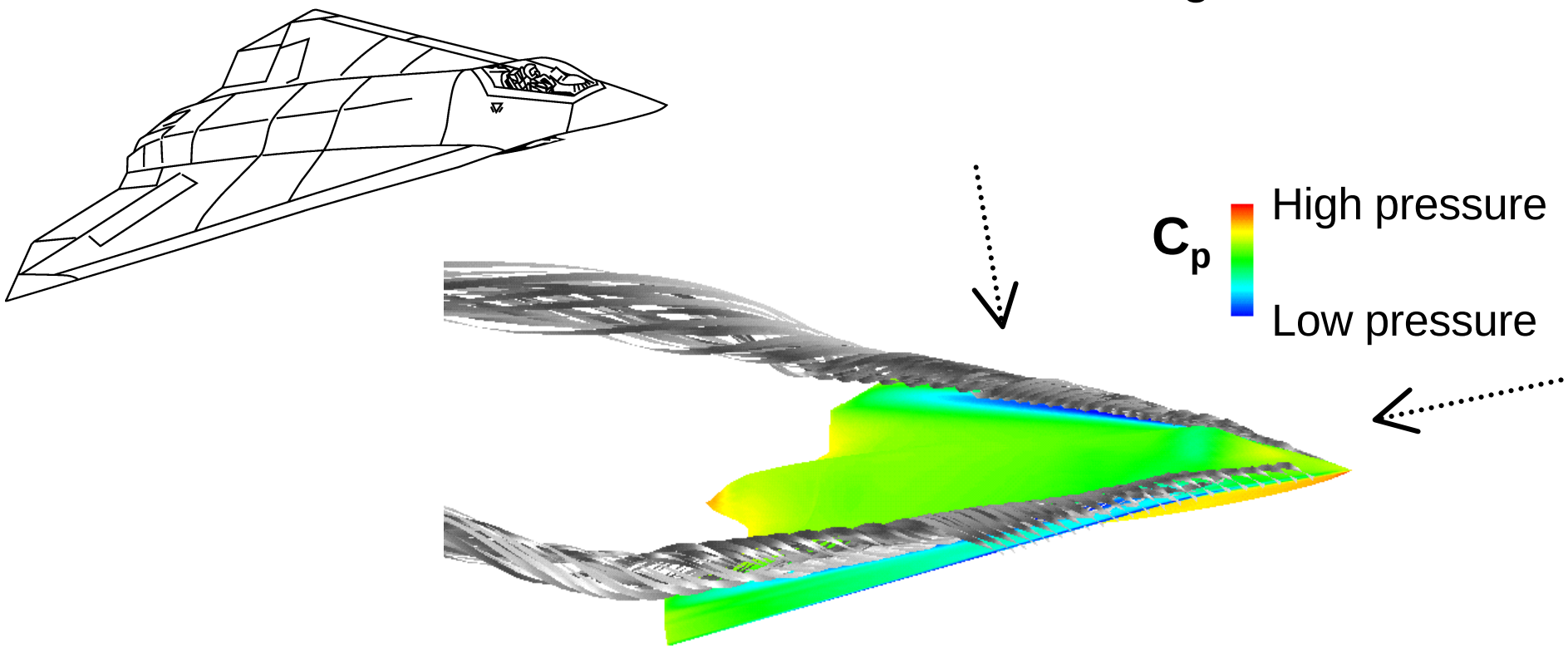
- Standard FORTRAN 77 source code
- User identifies the variables of the target differentiation

$$\frac{\partial Dependent}{\partial Independent}$$

- Reduces source code into elementary operations
  - e. g. SIN, COS, +, -, *, and /
- Traces dependencies through the program
- Generates new source code
  - Exact chain rule derivatives and original analysis
- User compiles and executes new derivative source code

Static Computational Flow Visualization CFL3D N-S S-A 0.6 Mach

- Characterize the flow structure (correlation)
- Pathlines seeded at leading edge of wing
- Color surface $\mathbf{C_p}$ contours
- Two views fixed to the configuration



Static Computational Flow Visualization

Attached flow

Bursting

30 deg α

25 deg α

20 deg α

Vortical

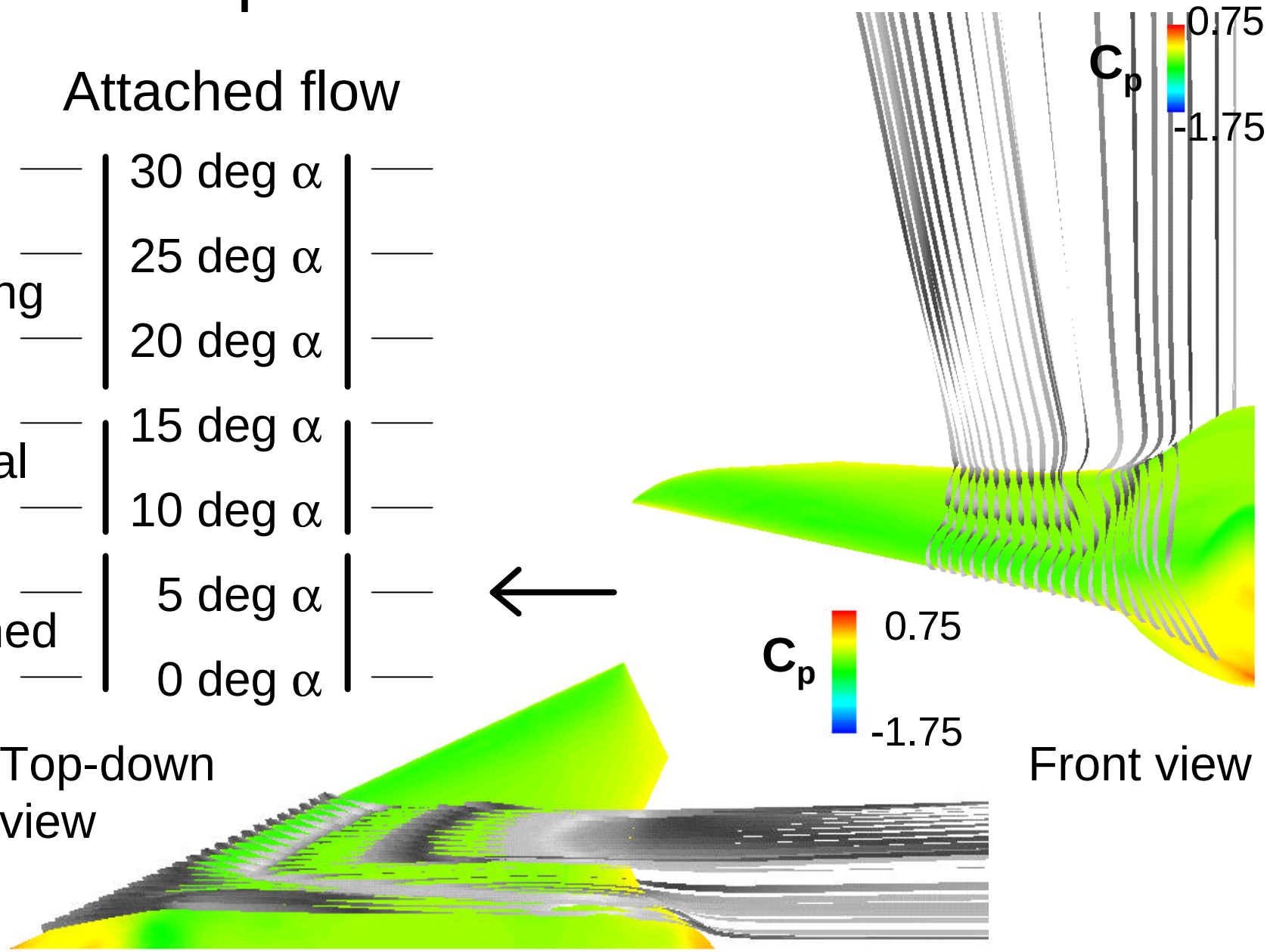
15 deg α

10 deg α

Attached

5 deg α

0 deg α



Top-down view

Front view

Static Computational Flow Visualization

Initial vortex flow

Bursting

30 deg α

25 deg α

20 deg α

Vortical

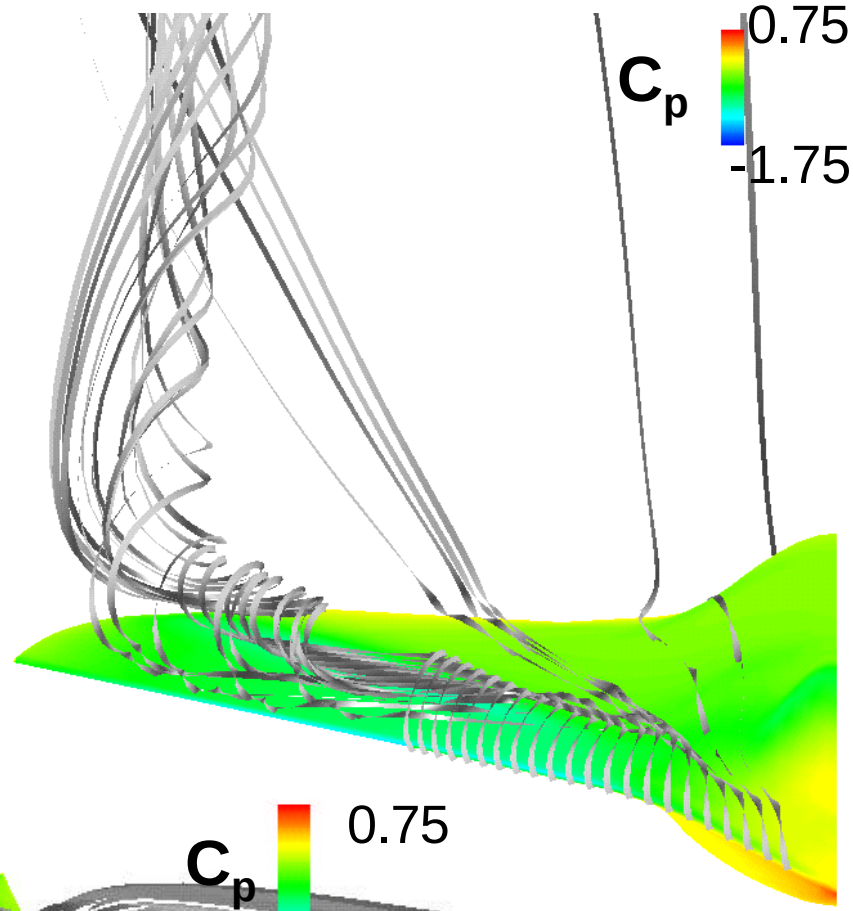
15 deg α

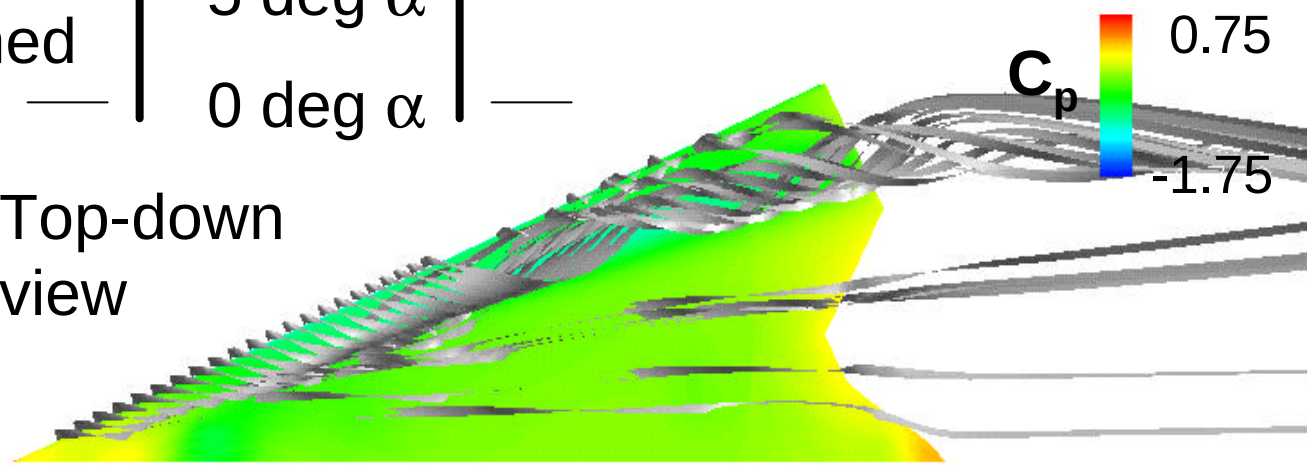
10 deg α

Attached

5 deg α

0 deg α





Top-down view

Front view

Static Computational Flow Visualization

Strong vortex flow

Bursting

30 deg α

25 deg α

20 deg α

Vortical

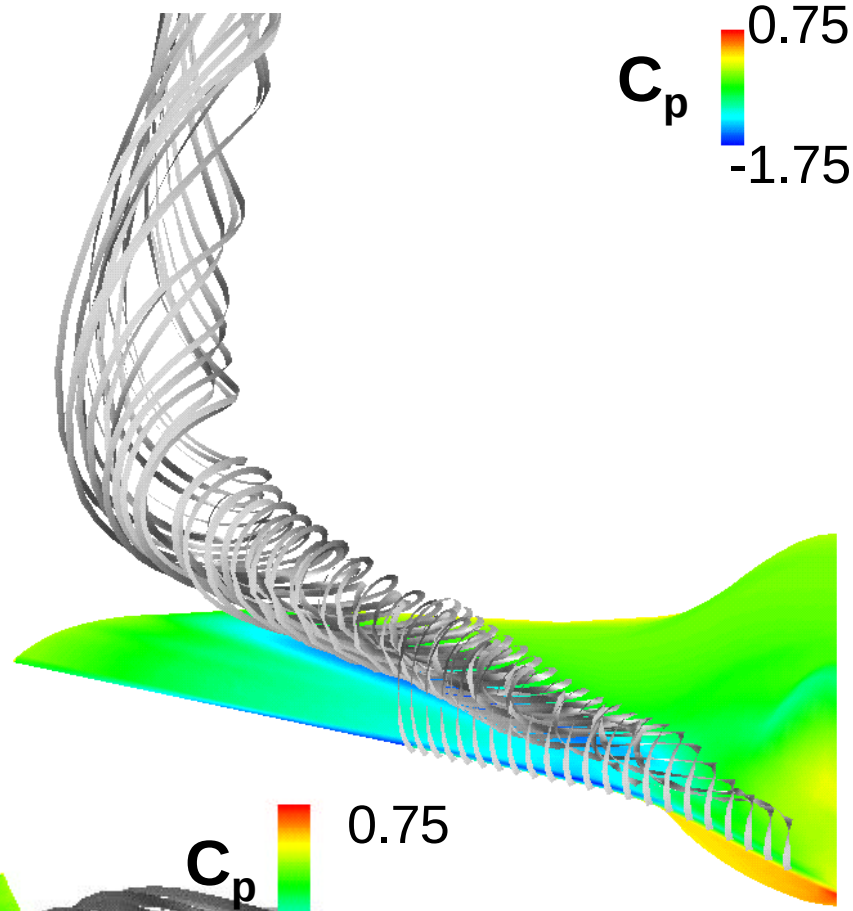
15 deg α

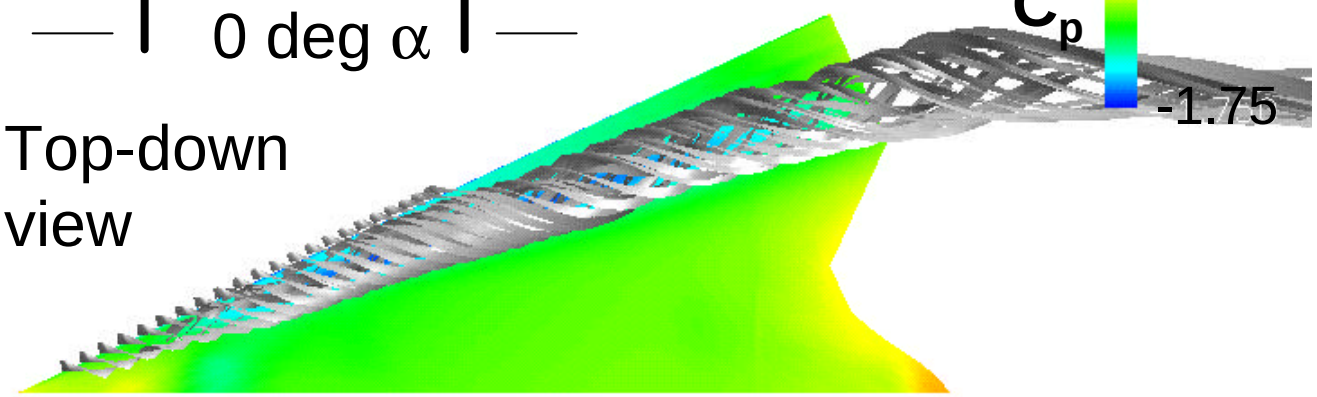
10 deg α

Attached

5 deg α

0 deg α





Top-down view

Front view

Static Computational Flow Visualization

Initial vortex burst

Bursting

30 deg α

25 deg α

20 deg α

Vortical

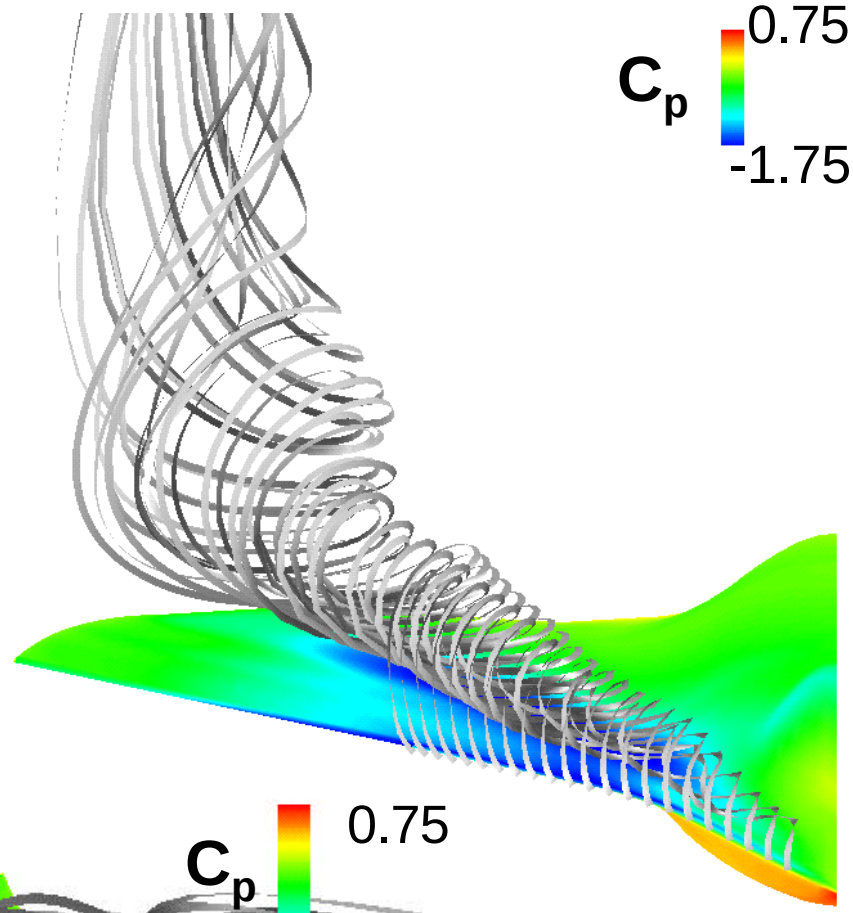
15 deg α

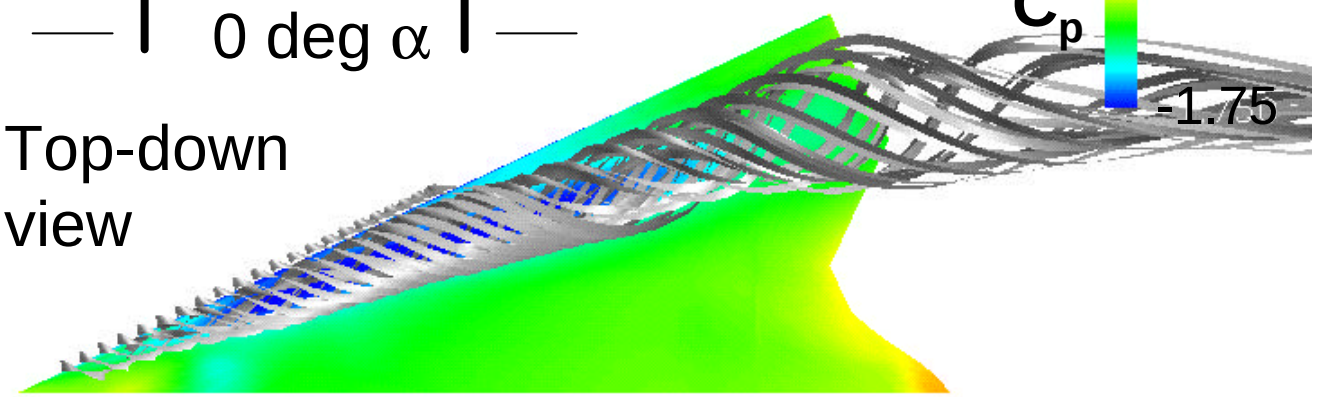
10 deg α

Attached

5 deg α

0 deg α





Top-down view

Front view

Static Computational Flow Visualization

Moderate vortex burst

Bursting

30 deg α

25 deg α

20 deg α

Vortical

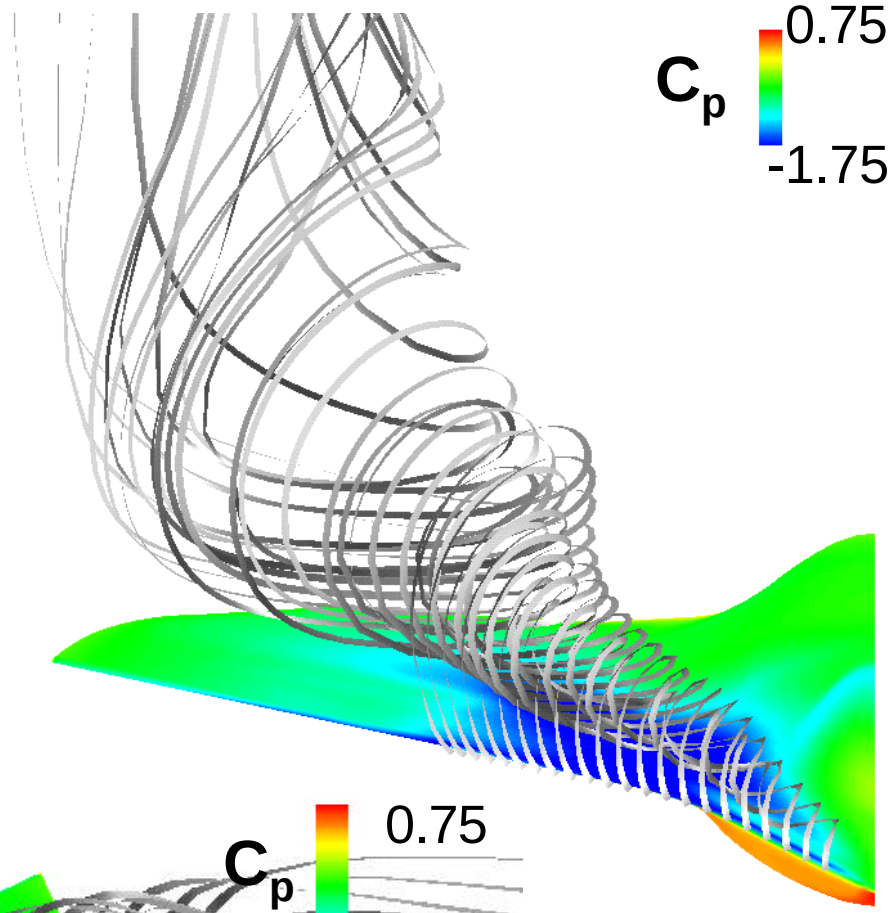
15 deg α

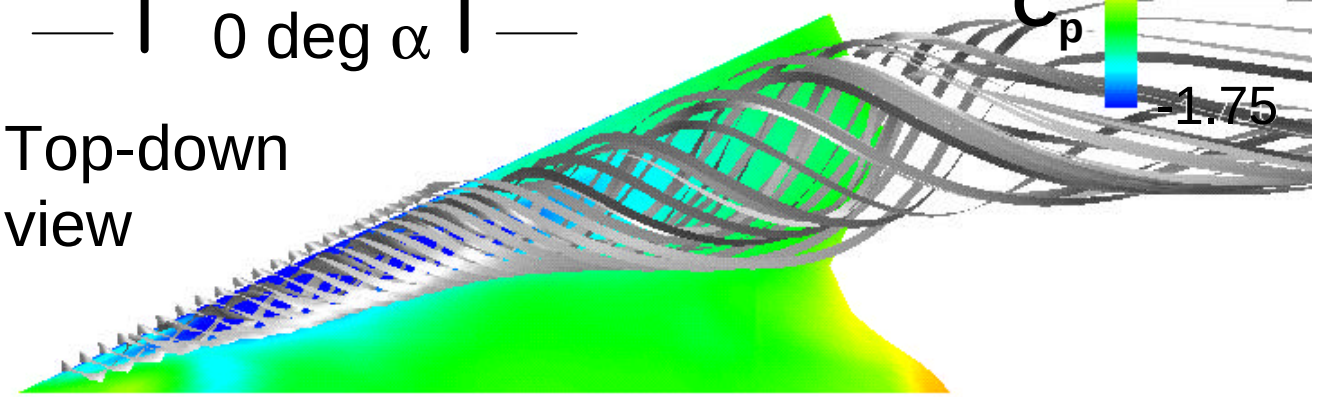
10 deg α

Attached

5 deg α

0 deg α





Top-down view

Front view

Static Computational Flow Visualization

Strong vortex burst

Bursting

30 deg α

25 deg α

20 deg α

Vortical

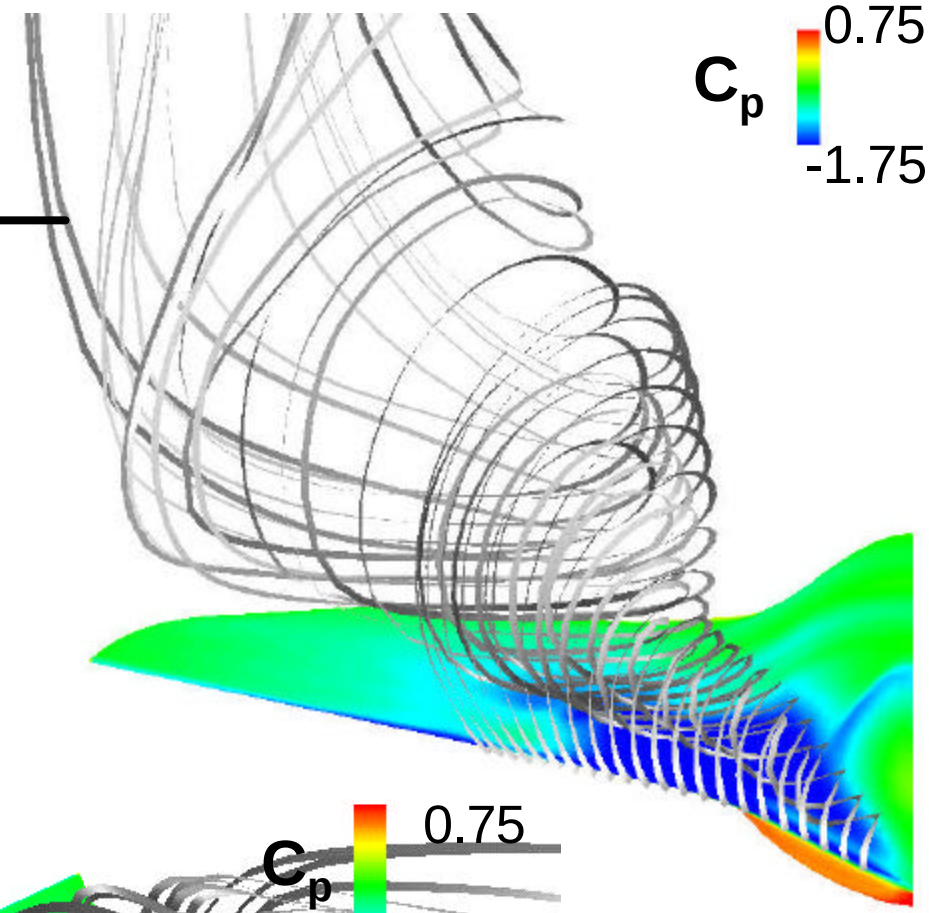
15 deg α

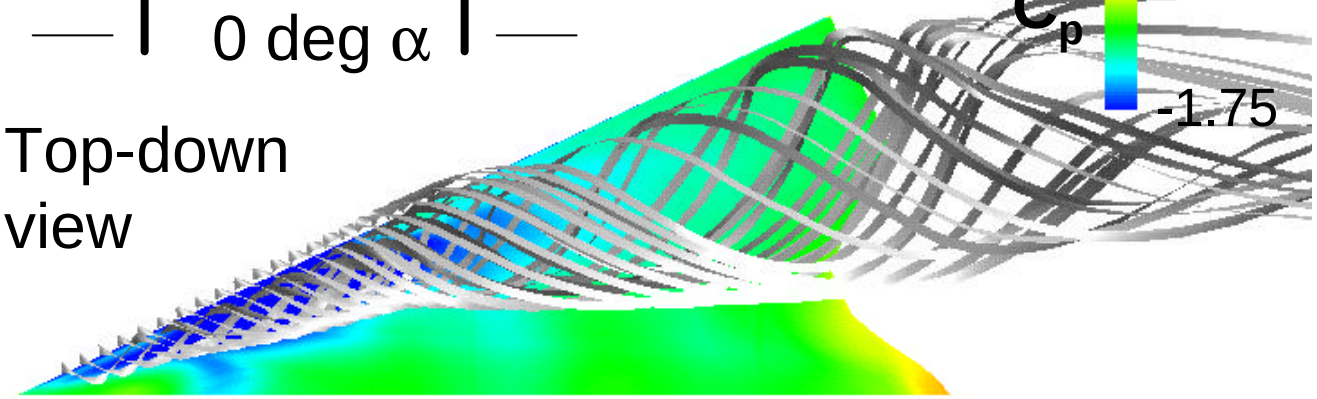
10 deg α

Attached

5 deg α

0 deg α

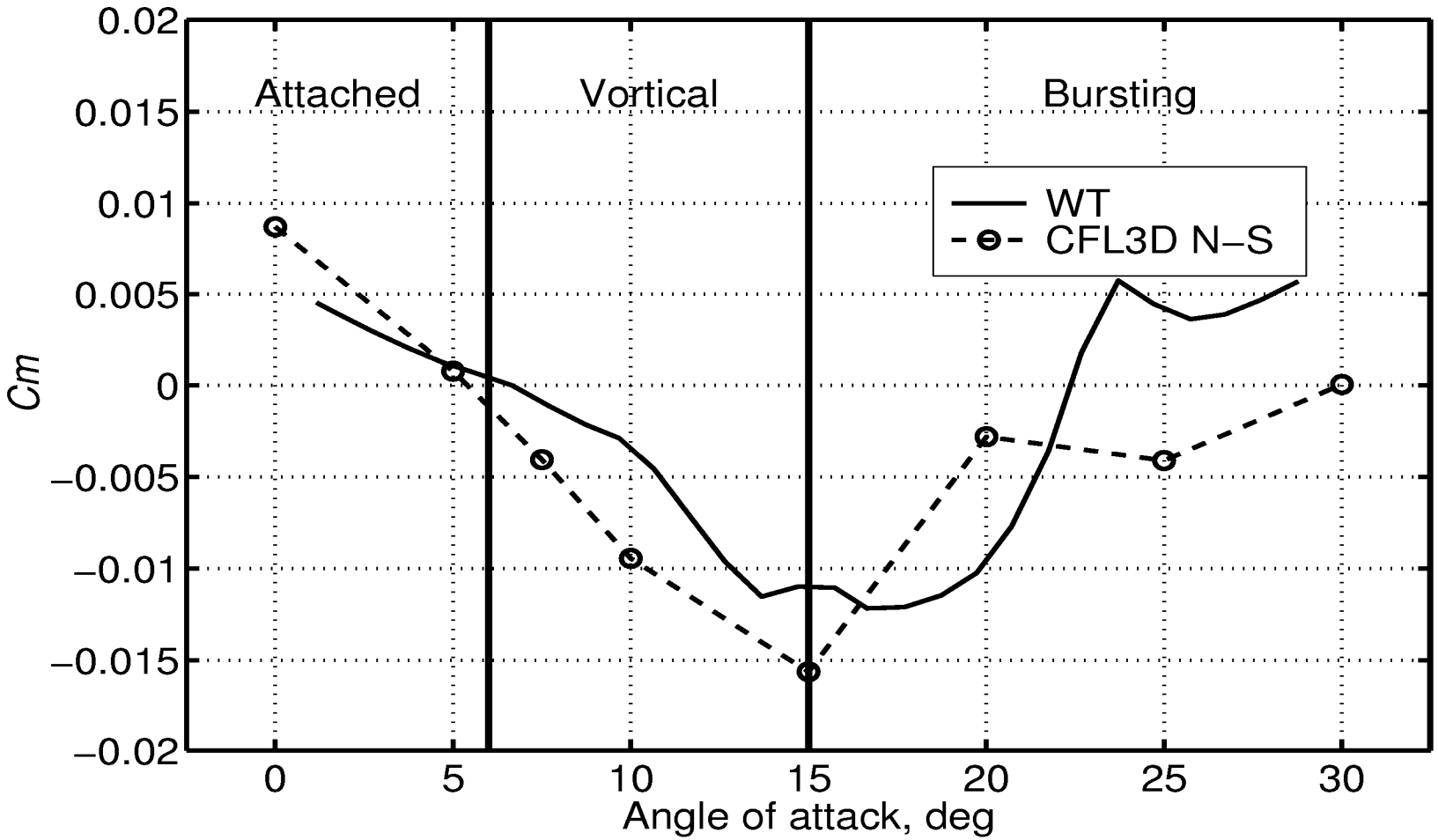




Top-down view

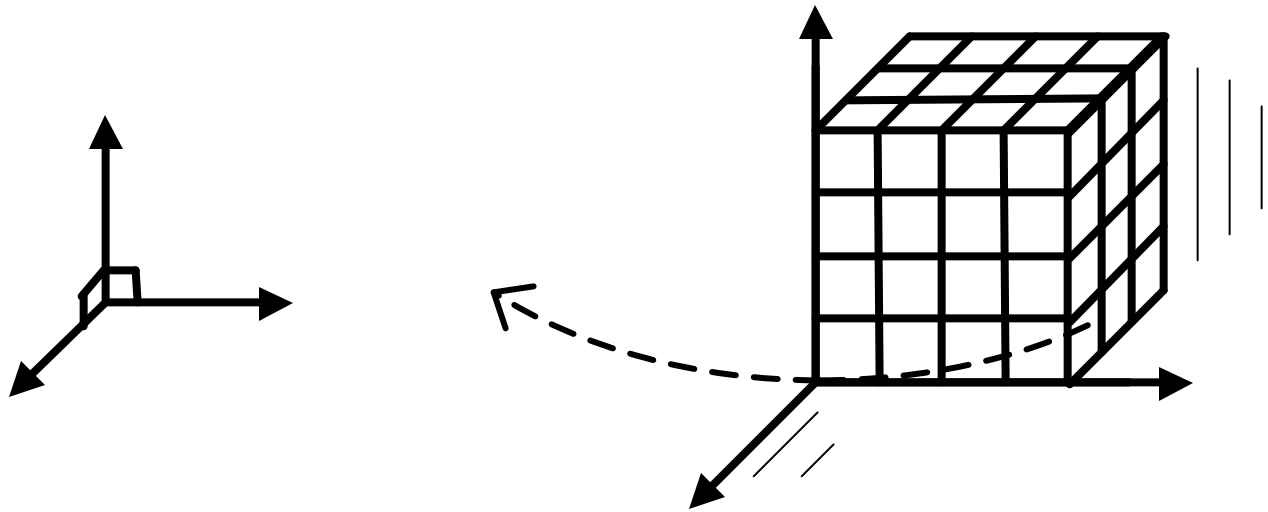
Front view

Three α ranges of flow structure
CFL3D N-S S-A 0.6 Mach



Angle of attack resolution: WT (~1 deg), CFD (~5 deg)

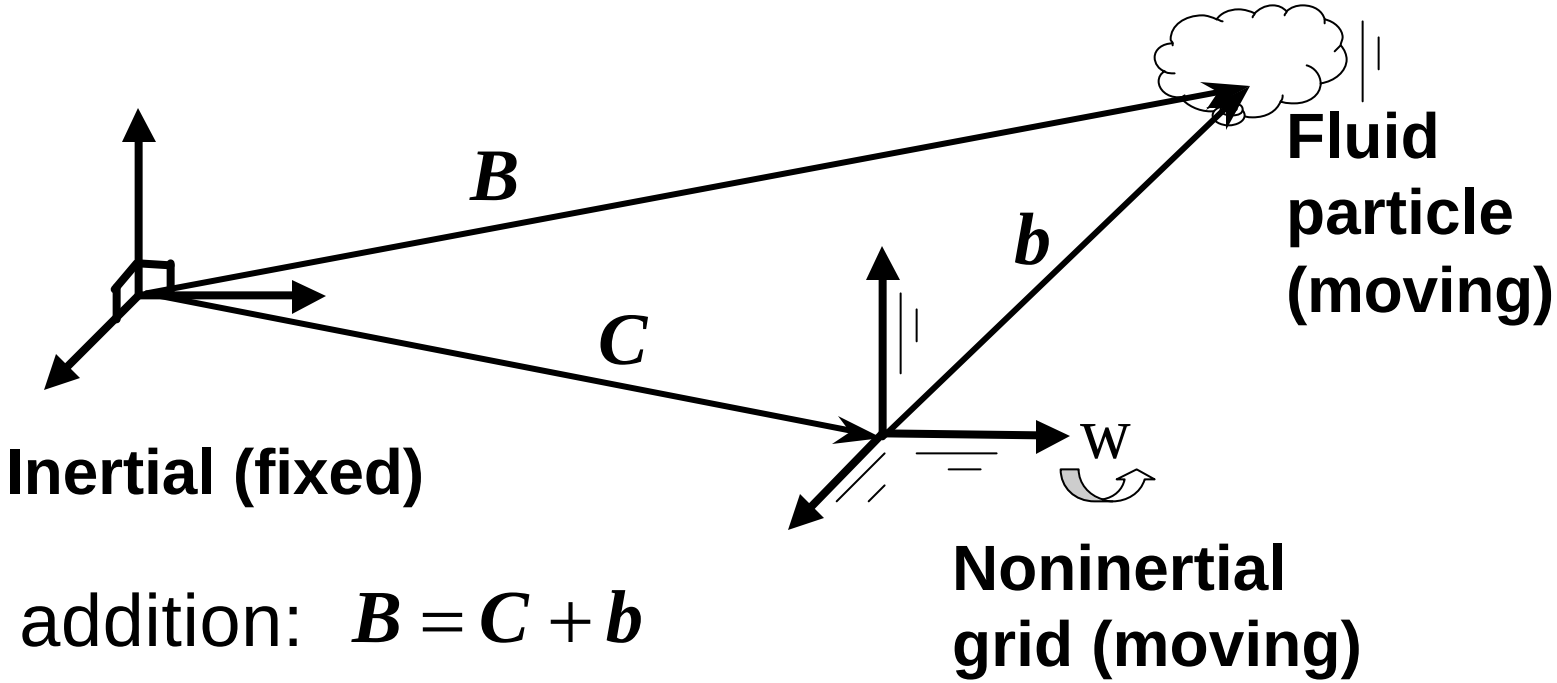
Noninertial Reference Frame



Inertial (fixed) **Noninertial CFD grid (moving)**

- Limache and Cliff approach (**AIAA 99-4313**)
- Efficient method to simulate moving CFD grids
  - Steady-state solutions of constant-rate motion
- Relatively simple to implement
  - **Add source term to N-S equations**
  - Increment boundary and initial conditions

Difference Between Reference Frames



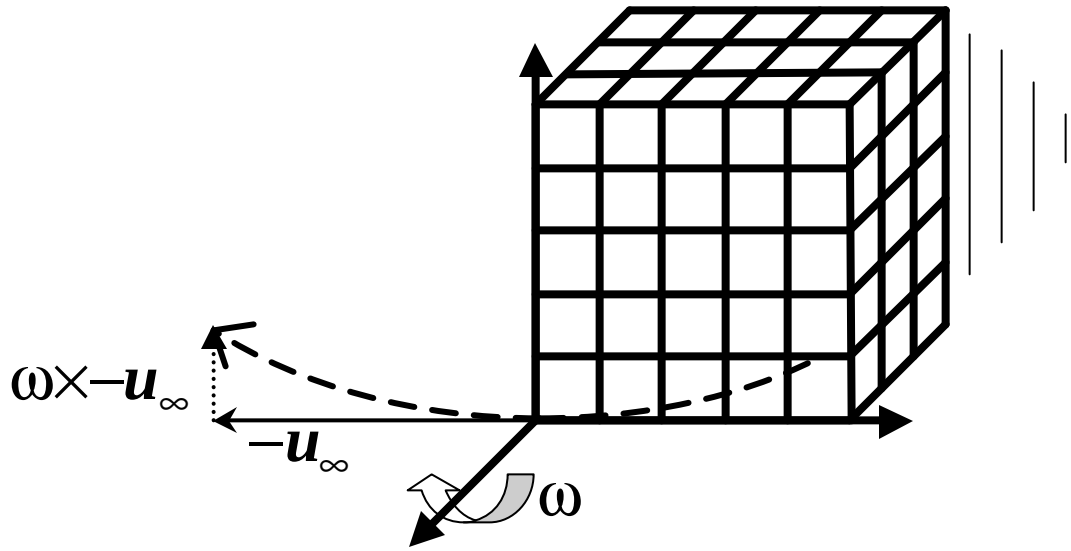
Vector addition: $\boldsymbol{B} = \boldsymbol{C} + \boldsymbol{b}$

1st derivative: $\dot{\boldsymbol{B}} = \dot{\boldsymbol{C}} + \dot{\boldsymbol{b}} + \omega \times \boldsymbol{b}$

2nd derivative: $\ddot{\boldsymbol{B}} = \ddot{\boldsymbol{C}} + \ddot{\boldsymbol{b}} + 2\omega \times \dot{\boldsymbol{b}} + \omega \times \left(\omega \times \boldsymbol{b}\right) + \dot{\omega} \times \boldsymbol{b}$

Difference: $\Theta = \ddot{\boldsymbol{B}} - \ddot{\boldsymbol{b}} = \ddot{\boldsymbol{C}} + 2\omega \times \dot{\boldsymbol{b}} + \omega \times \left(\omega \times \boldsymbol{b}\right) + \dot{\omega} \times \boldsymbol{b}$

Constant-Rate Simplification for Uniform Helical Motion



Constant-rate: $\dot{\omega} = 0$

Centripetal: $\ddot{\boldsymbol{c}} = \omega\times\dot{\boldsymbol{c}} = \omega\times-\boldsymbol{u}_\infty$

General difference: $\Theta = \ddot{\boldsymbol{c}} + 2\omega\times\dot{\boldsymbol{b}} + \omega\times\left(\omega\times\boldsymbol{b}\right) + \dot{\omega}\times\boldsymbol{b}$

Constant-rate: $\bar{\Theta} = \omega\times-\boldsymbol{u}_\infty + 2\omega\times\dot{\boldsymbol{b}} + \omega\times\left(\omega\times\boldsymbol{b}\right)$

CFL3D Noninertial Modifications

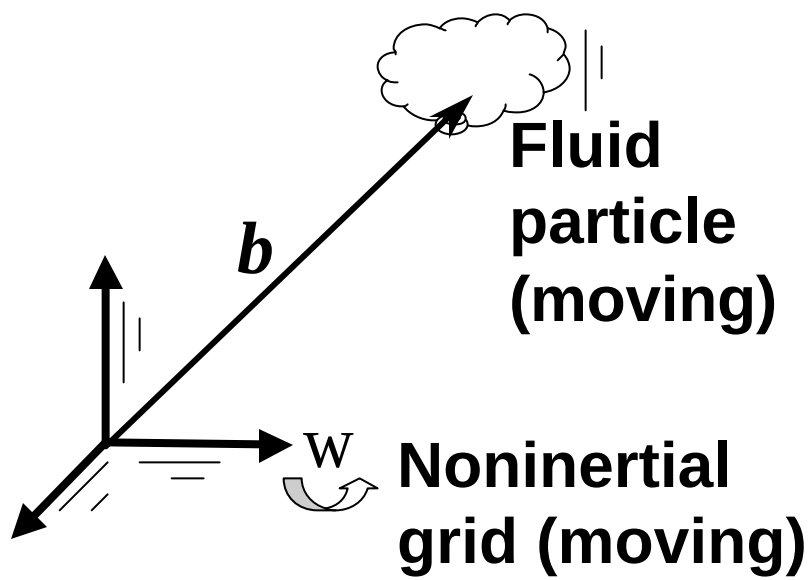
Solution update: $$\frac{1}{J}\frac{\partial \boldsymbol{Q}}{\partial t} = R(\boldsymbol{Q}) + \boldsymbol{S}$$

Conserved variables: $$\boldsymbol{Q} = \begin{bmatrix} \rho & \rho u & \rho v & \rho w & e \end{bmatrix}^T$$

Source term: $$\boldsymbol{S} = \frac{\rho}{J}\begin{bmatrix} 0 & \bar{\Theta}_x & \bar{\Theta}_y & \bar{\Theta}_z & \bar{\Theta}\,\mathbf{g}\cdot\mathbf{b} \end{bmatrix}^T$$

$$\frac{1}{J} = \text{Cell Volume}$$

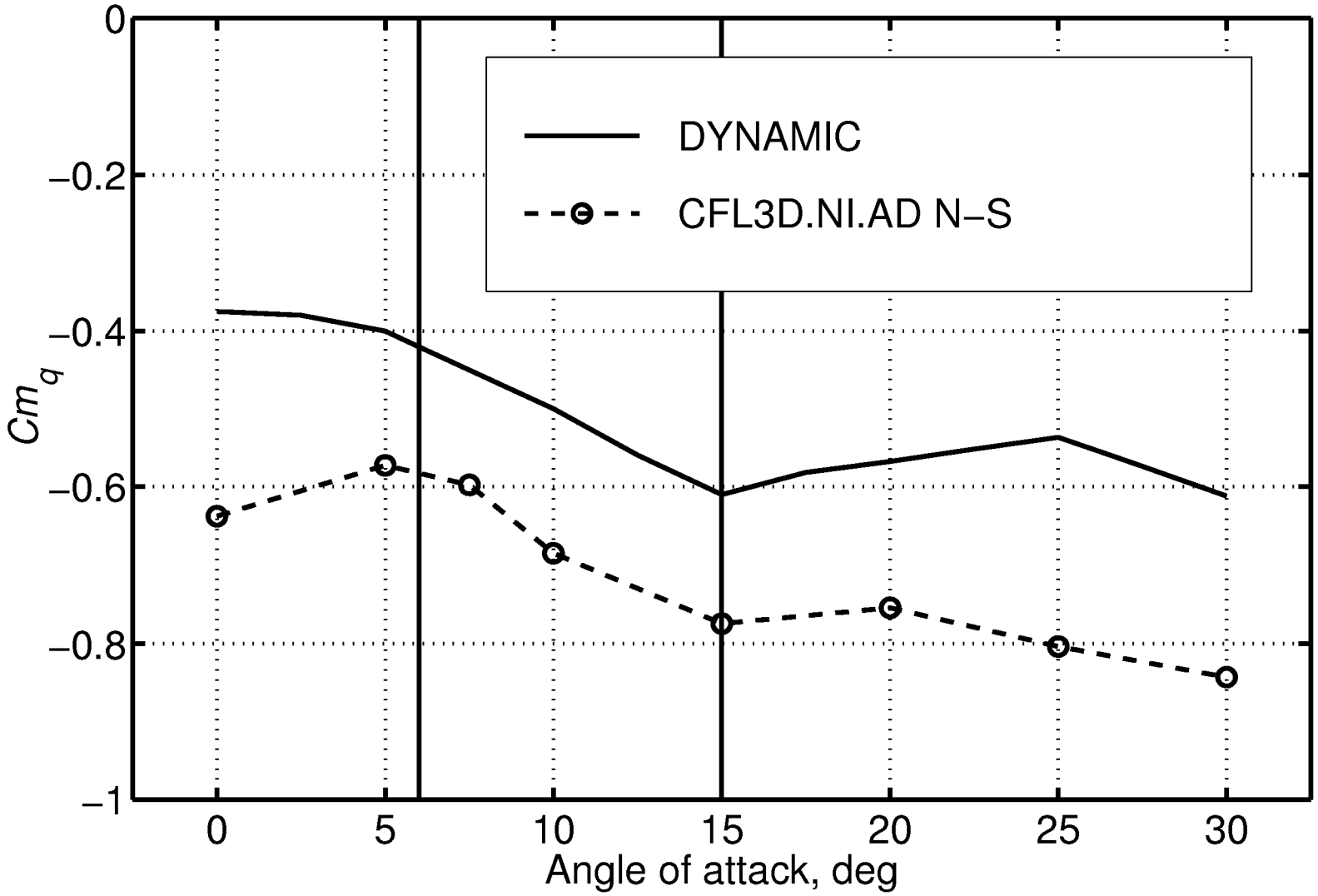
$$\mathbf{b} = \begin{bmatrix} u & v & w \end{bmatrix}$$



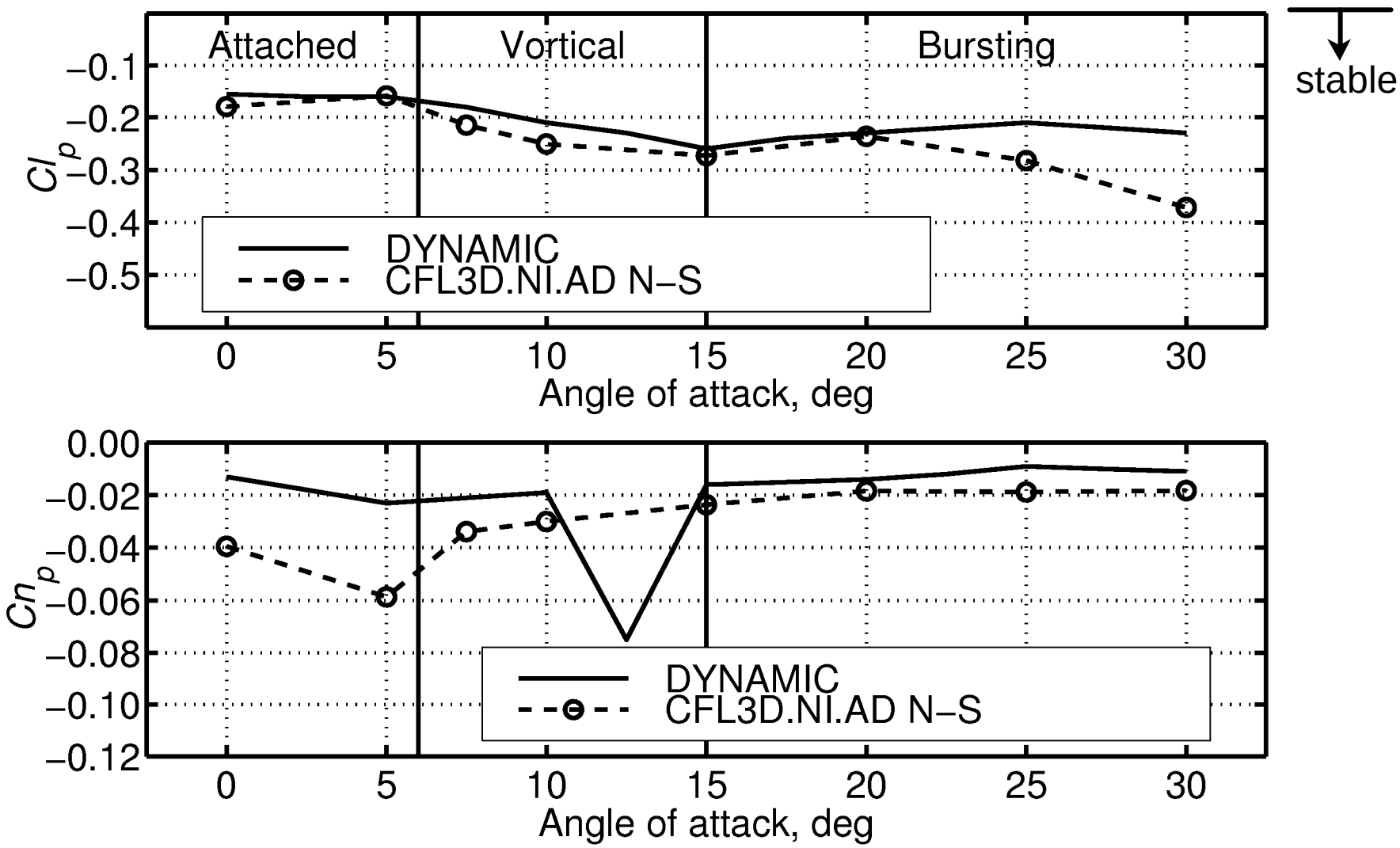
Dynamic Constant-Rate Derivatives

- No oscillatory data available
- CFL3D.NI.AD
  - ADIFOR-generated modified CFL3D
  - Convergence difficulties above 15 deg angle of attack
- DYNAMIC (Simon)
  - Dynamic rate derivative prediction code
  - Analytical strip theory
  - HASC
- HASC: High-Angle-of-Attack Stability and Control
  - Blake, et al
  - Vortex-lattice with empirical correction

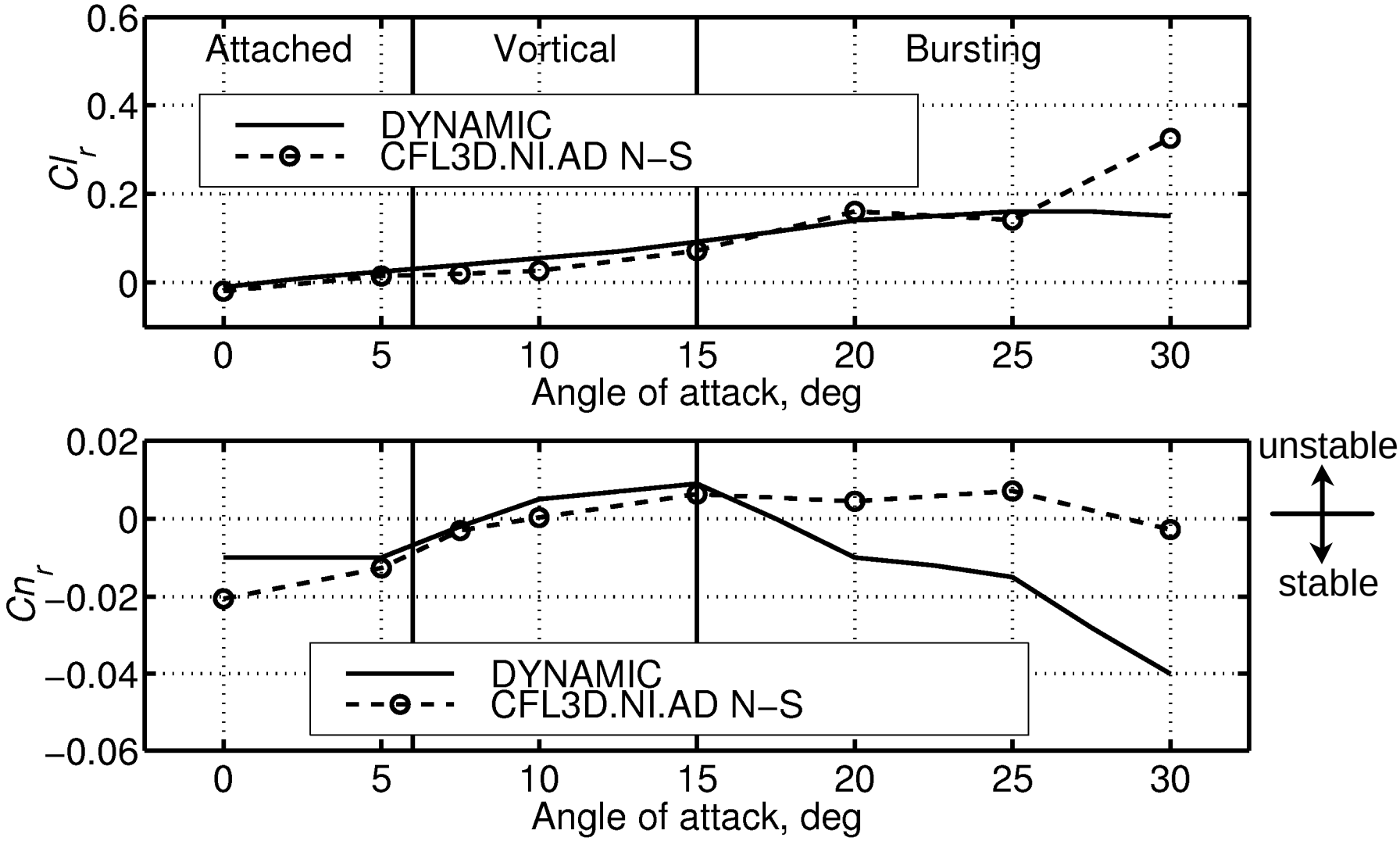
Pitch Rate Derivative CFL3D.NI.AD N-S S-A 0.6 Mach



Roll Rate Derivative CFL3D.NI.AD N-S S-A 0.6 Mach

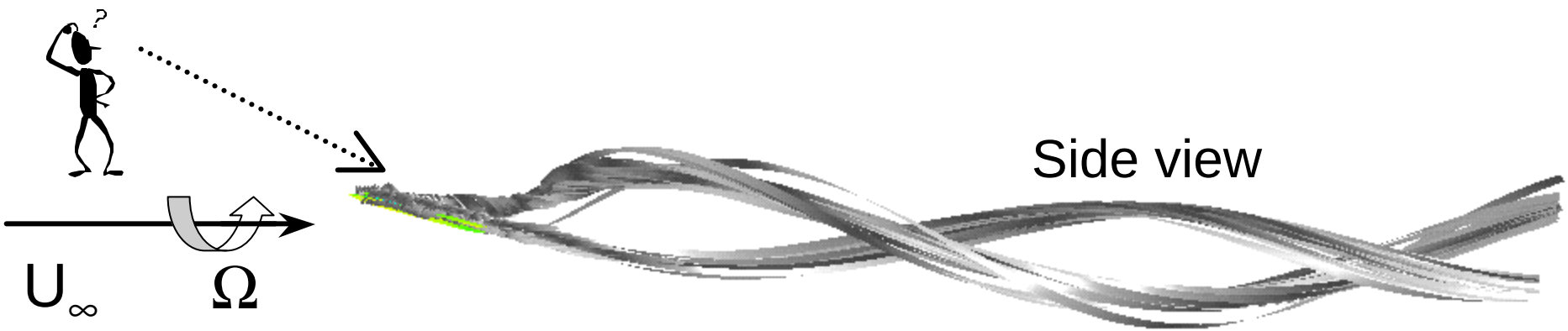


Yaw Rate Derivative CFL3D.NI.AD N-S S-A 0.6 Mach

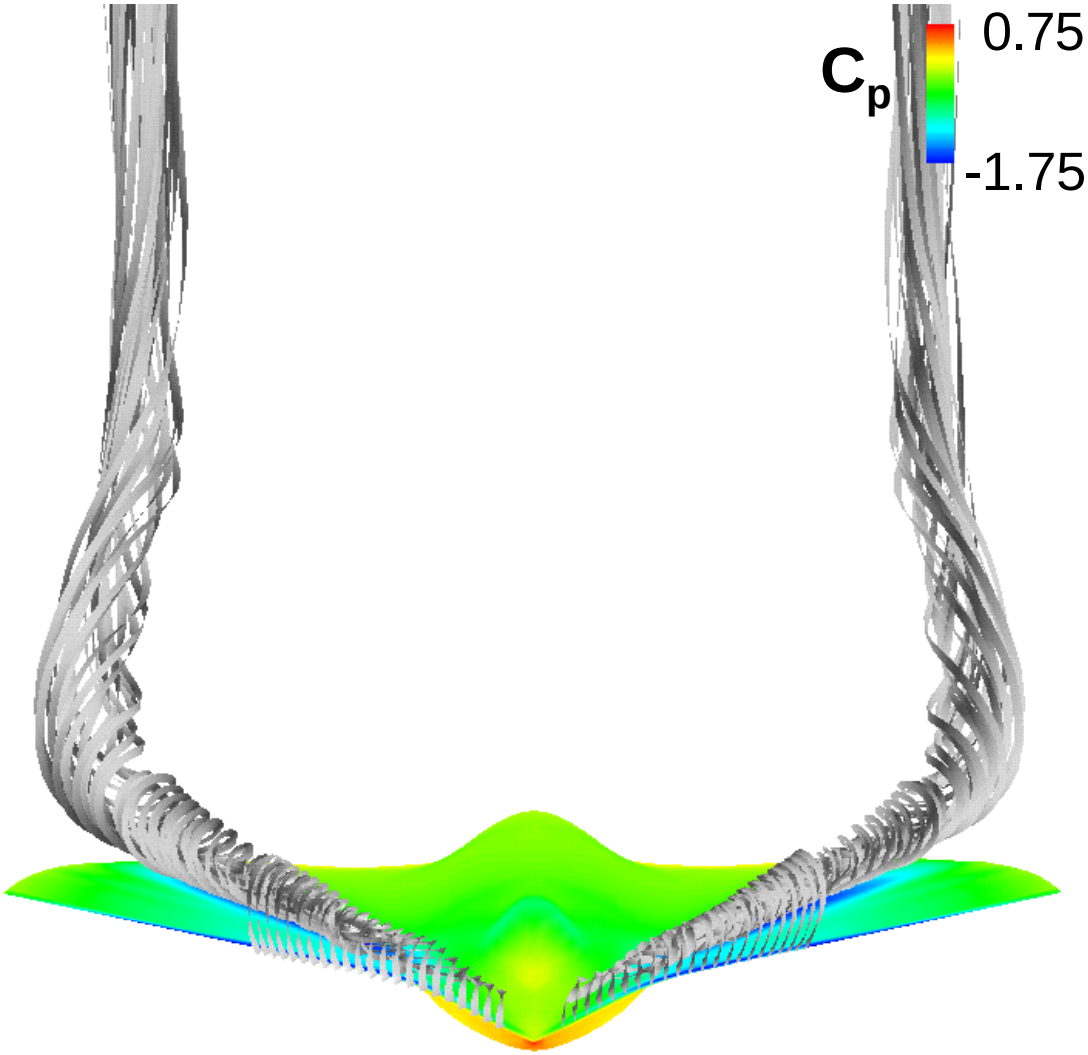


Rotary-Balance Simulation
CFL3D.NI N-S S-A 0.3 Mach, 15 α

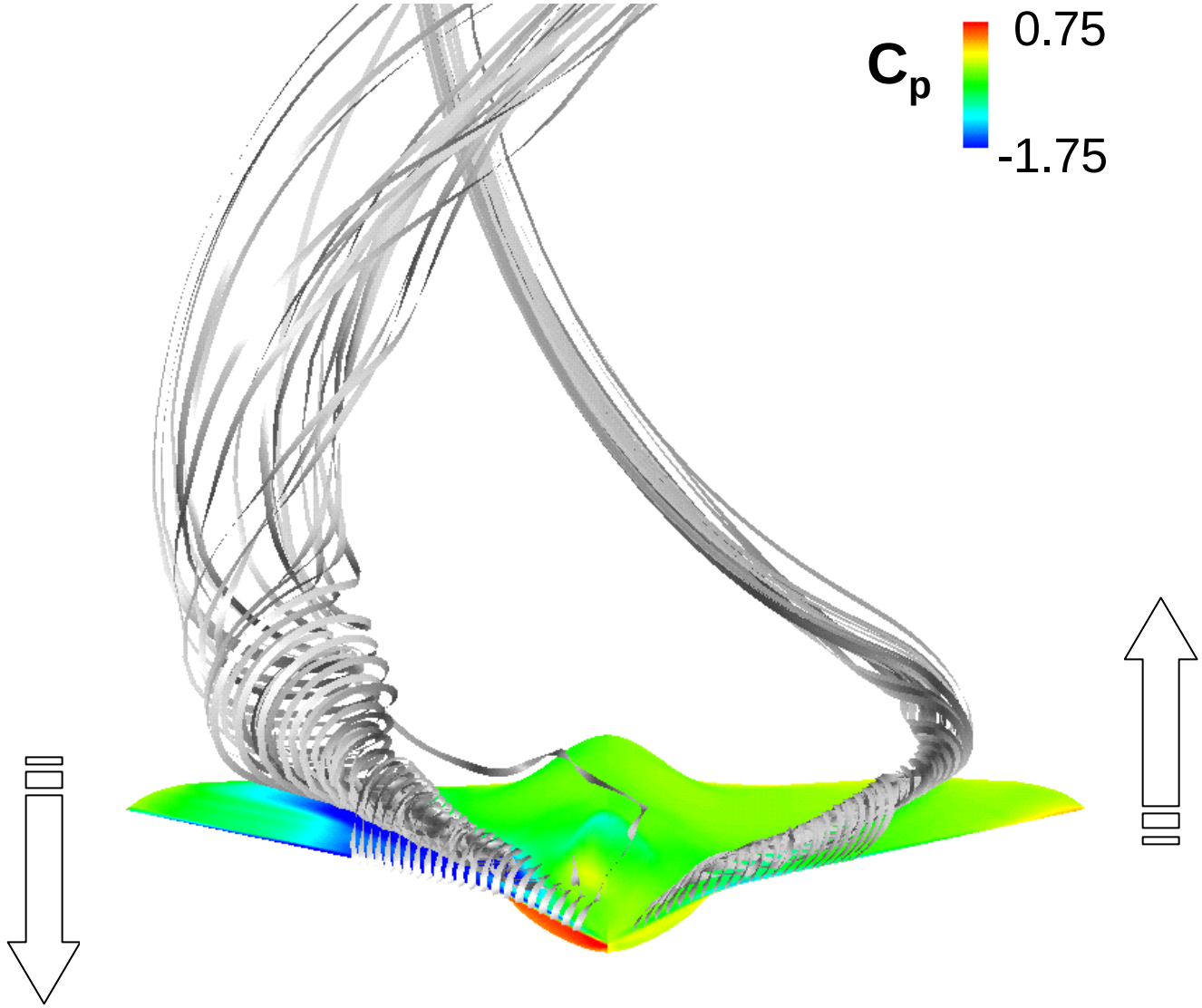
- CFL3D with noninertial modifications
- Rolls about the velocity vector
- Simulate rotary-balance wind tunnel test
- Ω = 0.0, **0.4**



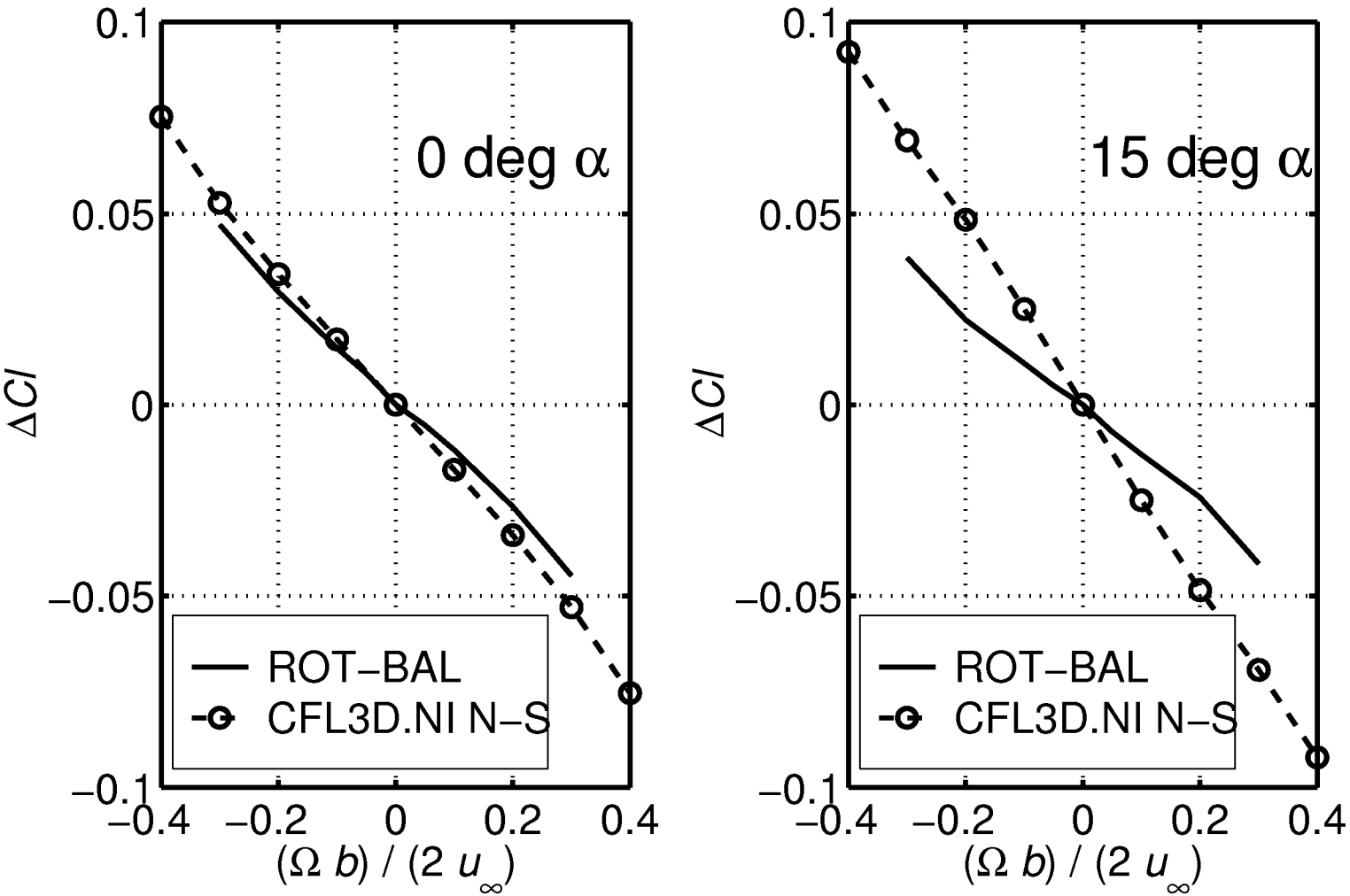
Rotary flow visualization $\Omega = 0.0$
CFL3D.NI N-S S-A 0.3 Mach, 15 α



Rotary flow visualization $\Omega = 0.4$
CFL3D.NI N-S S-A 0.3 Mach, 15 α



Rolling moment CFL3D.NI N-S S-A 0.3 Mach



Computational Resources
16-processor SGI Origin 2000™ (12 Gb)

- **Analysis only**
  - CFL3D, 0-15 deg α — **4** hr. per α case
  - CFL3D, >15 deg α — not performed
- **5 derivatives (a, b, *p*, *q*, *r*)**
  - Central differencing
    - CFL3D.NI 0-15 deg α — **44** hr. per α case
    - CFL3D.NI 0-15 deg α — not performed
  - ADIFOR-generated
    - CFL3D.NI.AD, 0-15 deg α — **30** hr. per α case
    - CFL3D.NI.AD, >15 deg α — **90** hr. per α case

Constant-rate noninertial calculations 3% increase

Summary and Conclusions

- Noninertial modifications for constant-rate steady-state solutions
- Static computational flow visualizations
  - Correlated to dynamic derivatives
- ADIFOR-generated modified CFL3D
  - Allow excellent extension to vortical flow
  - Difficulties with bursting structures (time-dependent)
  - 30% faster than central differencing (5 independents)
  - Constant-rate noninertial calculations 3% increase
  - Rotating-grid time-accurate can require an order of magnitude increase in execution time

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