AIAA 99-3136

Determination of Stability and Control Derivatives Using Computational Fluid Dynamics and Automatic Differentiation

Michael A. Park
George Washington University
Joint Institute for the Advancement of Flight Sciences
(JIAFS)

Lawrence L. Green, Raymond C. Montgomery,
and David L. Raney
NASA Langley Research Center, Hampton, Virginia

Outline

- Introduction / motivation - stability and control derivatives from CFD
- Example configuration - LMTAS-ICE
- Sensitivity methods - Automatic Differentiation (AD)
- CFD codes - PMARC / CFL3D
- AD validation
- Results
  - ADIFOR - Static stability derivatives
  - ADJIFOR - Control effectiveness derivatives
- Conclusions

Introduction / motivation

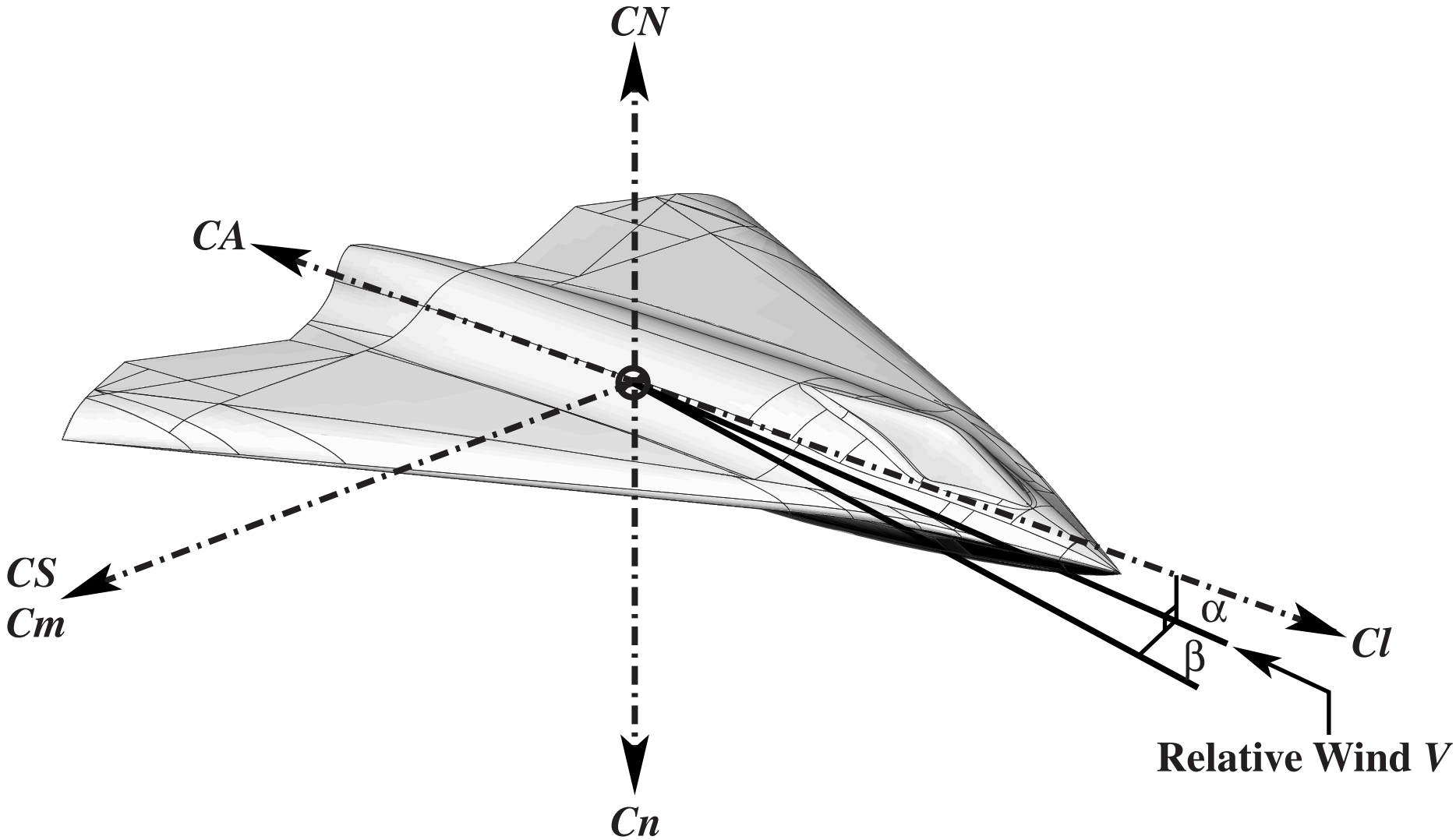
- Stability and control derivatives (S&C)
  - Linear models - simulation and control law design
  - Derivatives of aircraft forces and moments
    - Angle of attack (α) - CN_α, CA_α, Cm_α
    - Angle of sideslip (β) - CS_β, Cl_β, Cn_β
    - Normal deflections of grid surface (Xn)
      - Cl_{Xn}, Cm_{Xn}, Cn_{Xn}
- Experimental computational determination
  - Faster, cheaper, unique capabilities
  - Incorporation in multidisciplinary design

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

- Concept vehicle to explore stealth and controllability
- Tailless with highly swept, sharp leading edges
- Wind tunnel (WT) data
  - Low speed, transonic, and supersonic
  - Large α, β range
  - Conventional / novel control effectors
- ADIFOR-CFD Studies
  - Mach = 0.6, $Re_{\mathbf{MAC}}$ = 4.0M
  - Limited α, β range
  - Novel shape change effectors

Example configuration

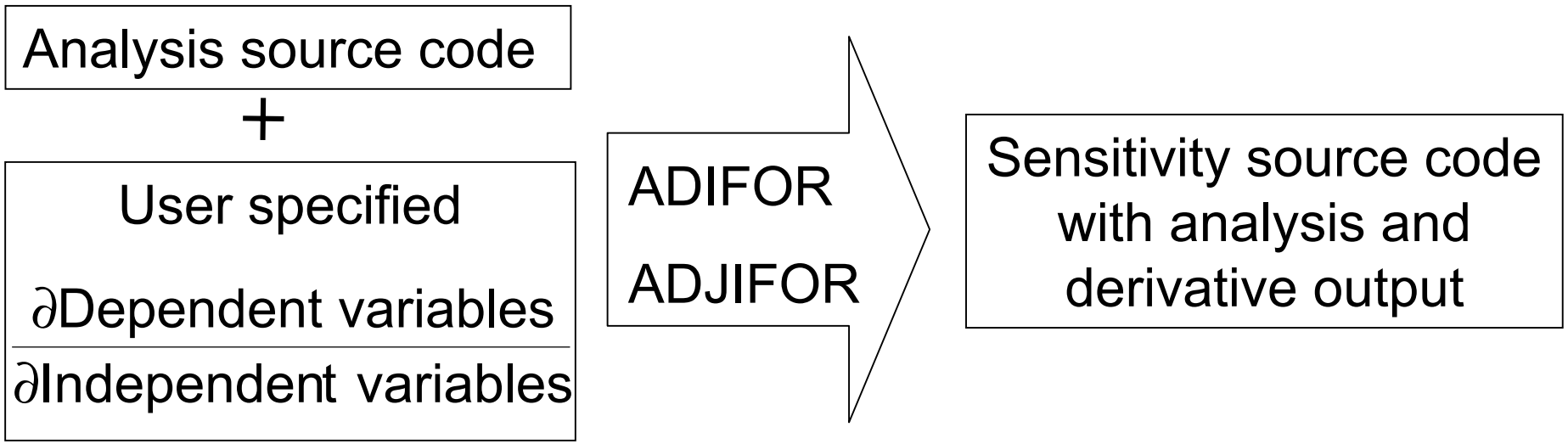
Lockheed-Martin Tactical Aircraft Systems - Innovative Control Effectors (ICE)



Sensitivity methods

- Central finite difference (CD) approximations
  - Step size dependent
- Automatic Differentiation (AD)
  - Exact
  - Augment source code to produce user specified derivatives
    - Chain rule of calculus
    - Adjoint formulation

ADIFOR / ADJIFOR



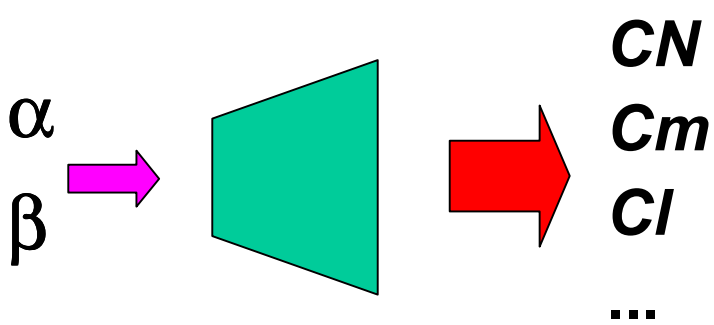
- ADIFOR 3.0 package
  - ADIFOR (Automatic Differentiation of FORTRAN)
  - ADJIFOR (Automatic Adjoint Formulation in FORTRAN)
  - Rice University, Argonne National Laboratory

ADIFOR

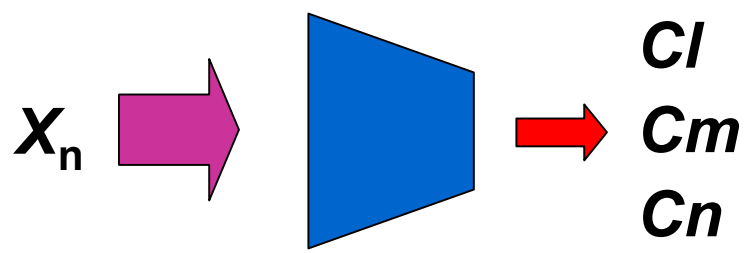
- "Forward mode"
- Chain rule of calculus
- Step-by-step propagation through elementary pieces of the code
- Best for more dependent than independent variables

ADJIFOR

- "Reverse Mode"
- Discrete adjoint formulation
- Backward propagation of adjoints through the code
- Best for more independent than dependent variables



Ref. AIAA 94-2197



Ref. AIAA 98-4807

CFD Codes
PMARC (Panel Method Ames Research Center)

- Ashby - NASA Ames Research Center
- Constant doublet and source strength over each panel

- No compressibility or boundary layer corrections used
- 2560 panel full span model

- NASA-LaRC HPCCP / CAS Origin 2000

CFD Codes
CFL3D (Computational Fluids Laboratory 3-Dimensional)

- Thomas, et al - NASA Langley Research Center
- Euler and turbulent Navier-Stokes (N-S)
- Parallel execution (MPI)

- Euler and N-S Spalart-Allmaras (S-A) cases performed
- Euler 3.1 M grid points full span Long. + Lat.
- N-S 1.6 M grid points half span Long.

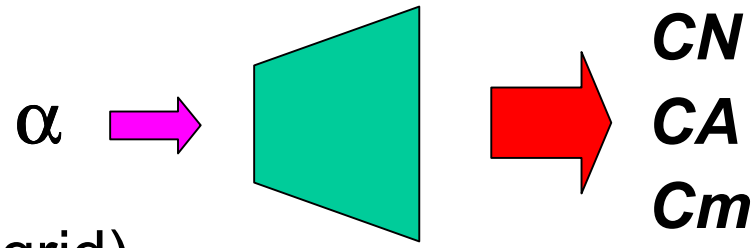
- NASA-LaRC HPCCP/CAS Origin 2000
- Grid - GEOLAB

AD Validation

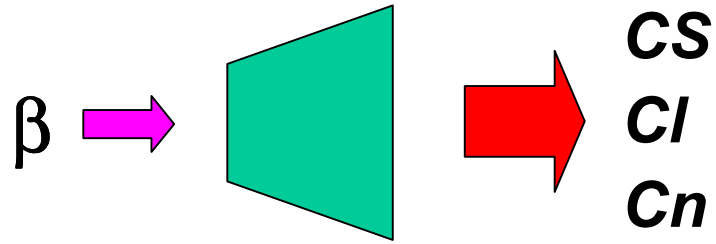
- The forces and moments from the AD-CFD codes
  - Matched the original CFD codes
  - Compared favorably with WT data
    - Lateral WT asymmetry observed above 5 deg angle of attack
    - Affects CD-WT derivatives
- AD-CFD derivatives
  - Matched CD of the CFD codes
  - Compared with CD of the WT data

ADIFOR Results
Static stability derivatives

- Longitudinal
  - CD - WT
  - ADIFOR - PMARC
  - ADIFOR - CFL3D
    - Euler (medium and fine grid)
    - N-S S-A (half span fine grid)

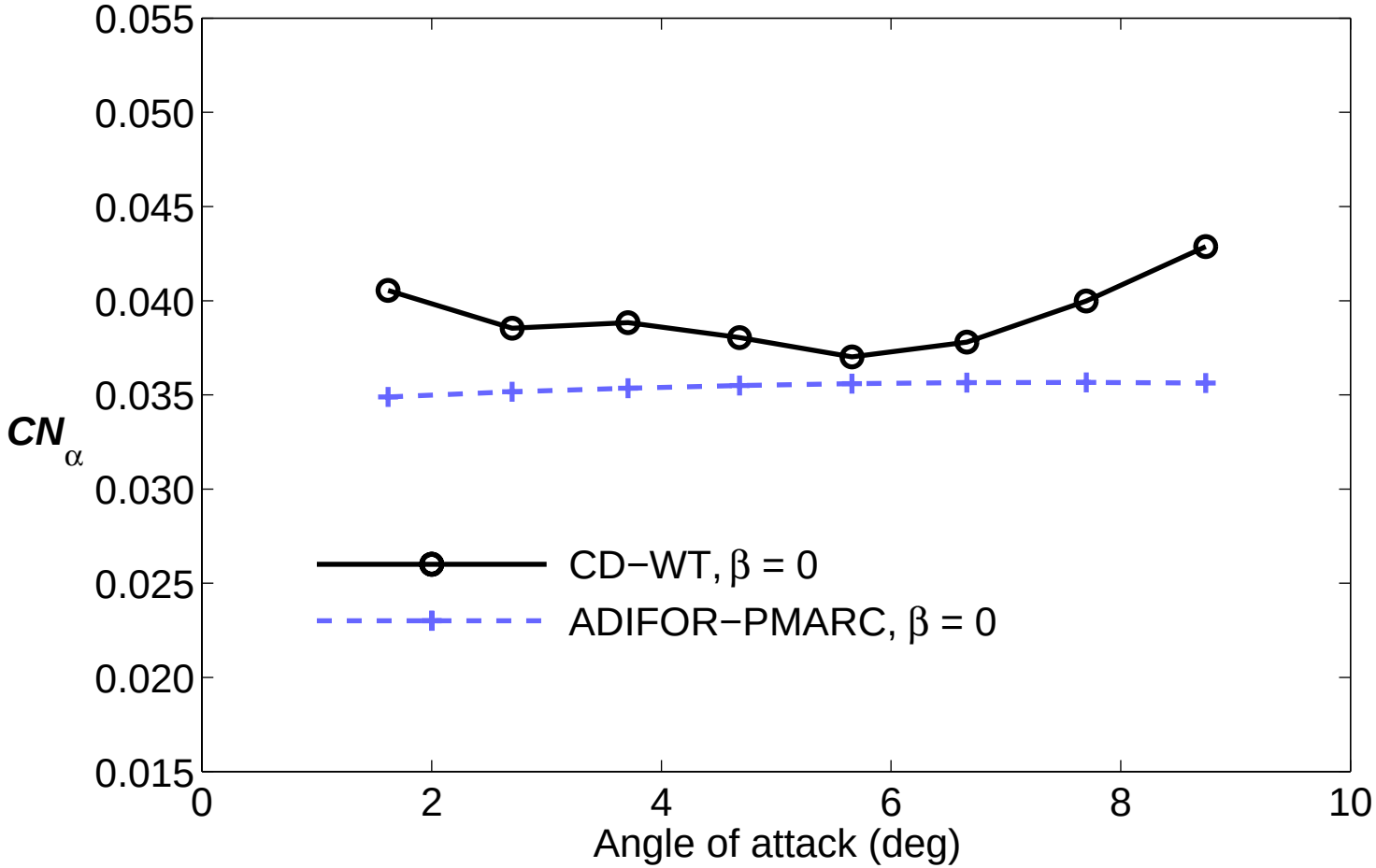


- Lateral
  - CD - WT
  - ADIFOR - PMARC
  - ADIFOR - CFL3D
    - Euler (medium and fine grid)



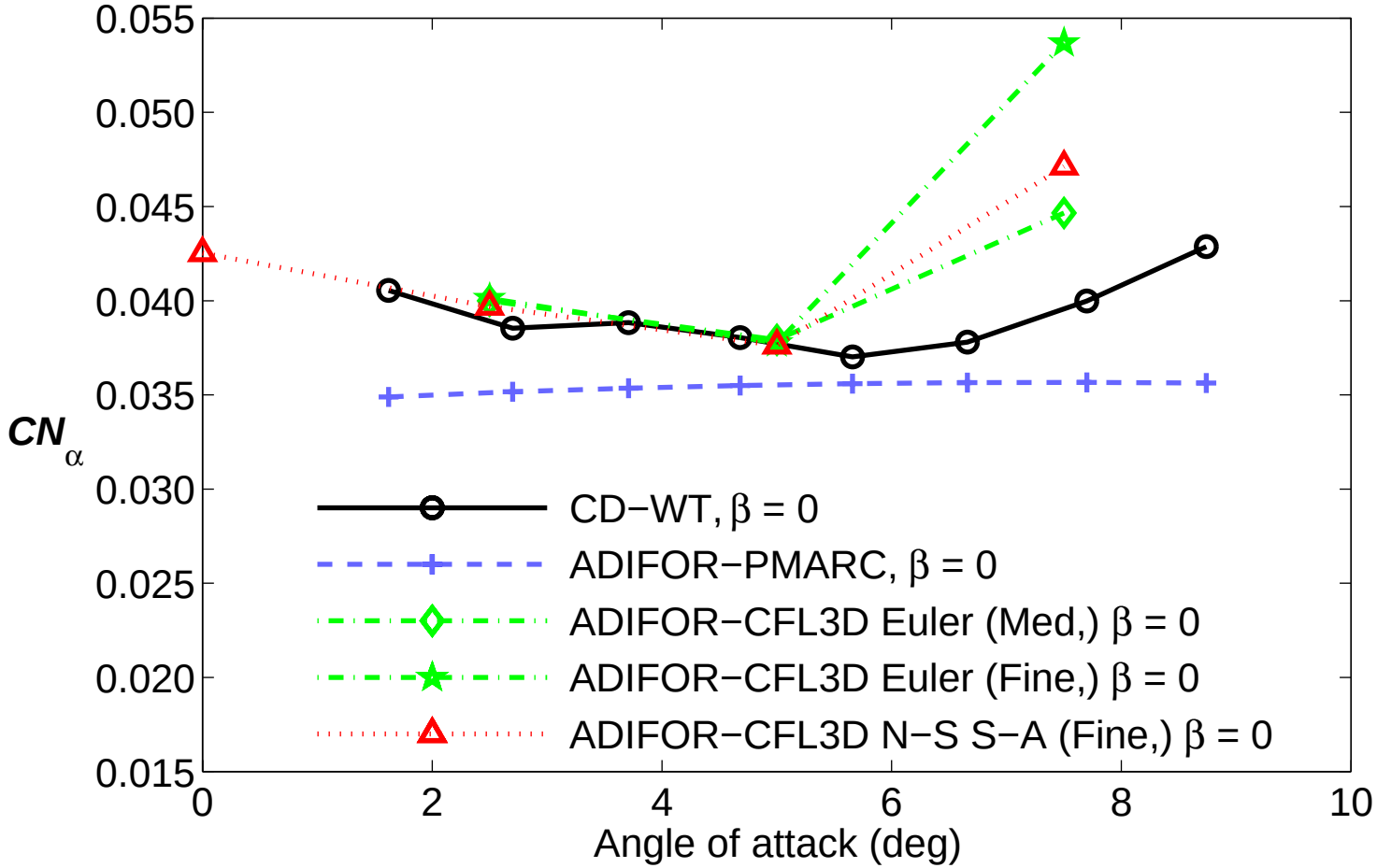
ADIFOR Results

Normal force coefficient α derivative (M=0.60)



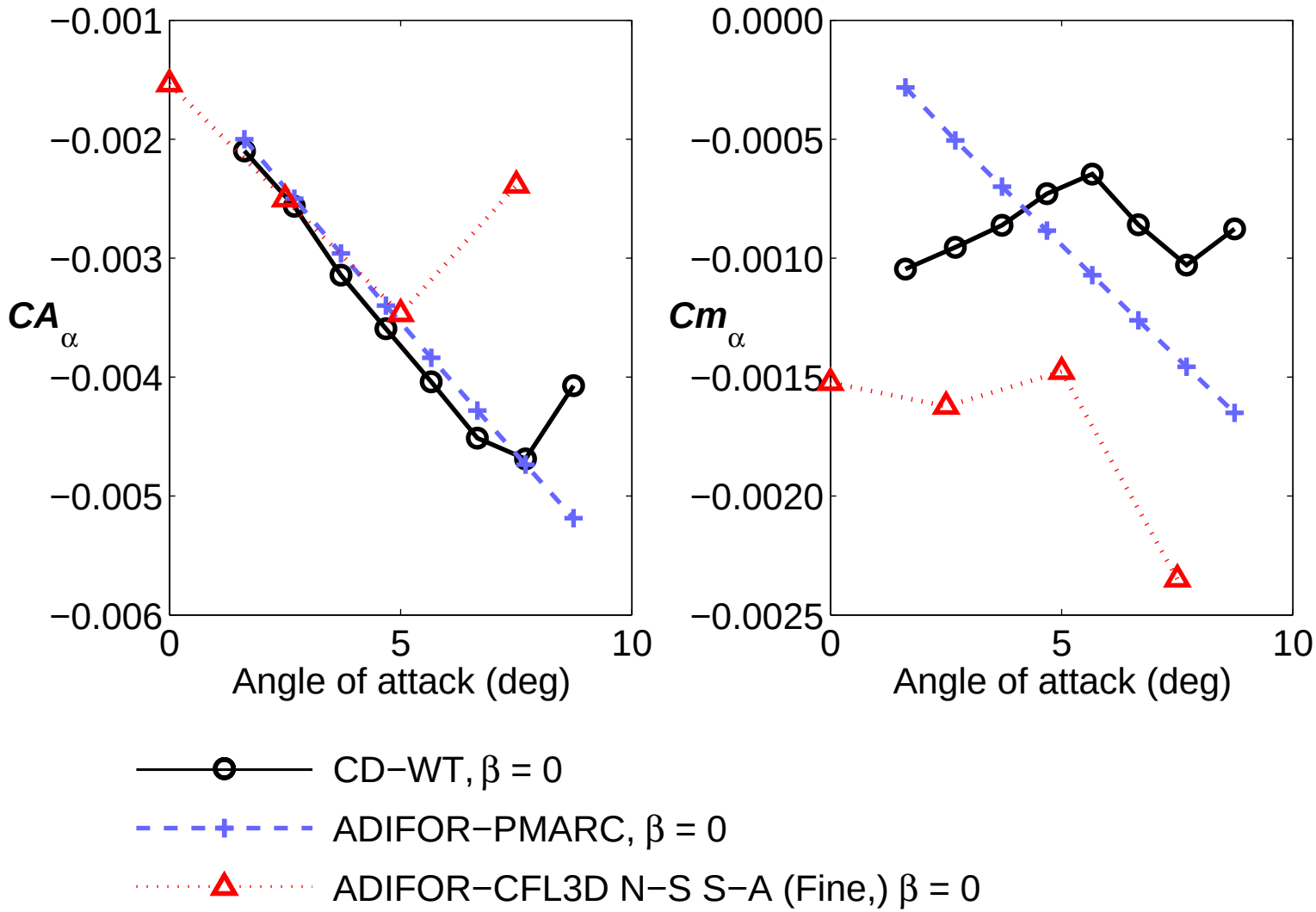
ADIFOR Results

Normal force coefficient α derivative (M=0.60)



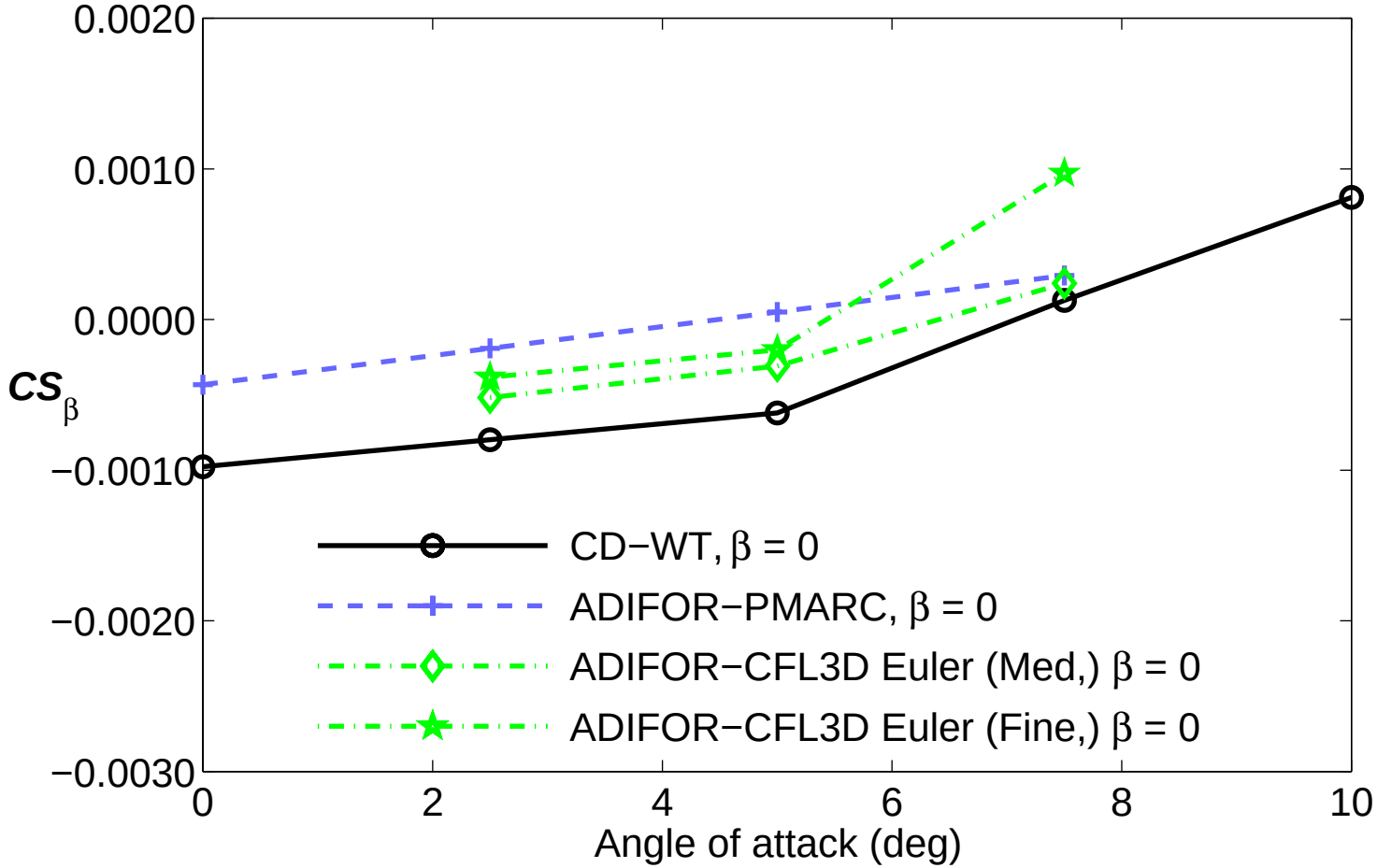
ADIFOR Results

Longitudinal α derivatives (M=0.60)



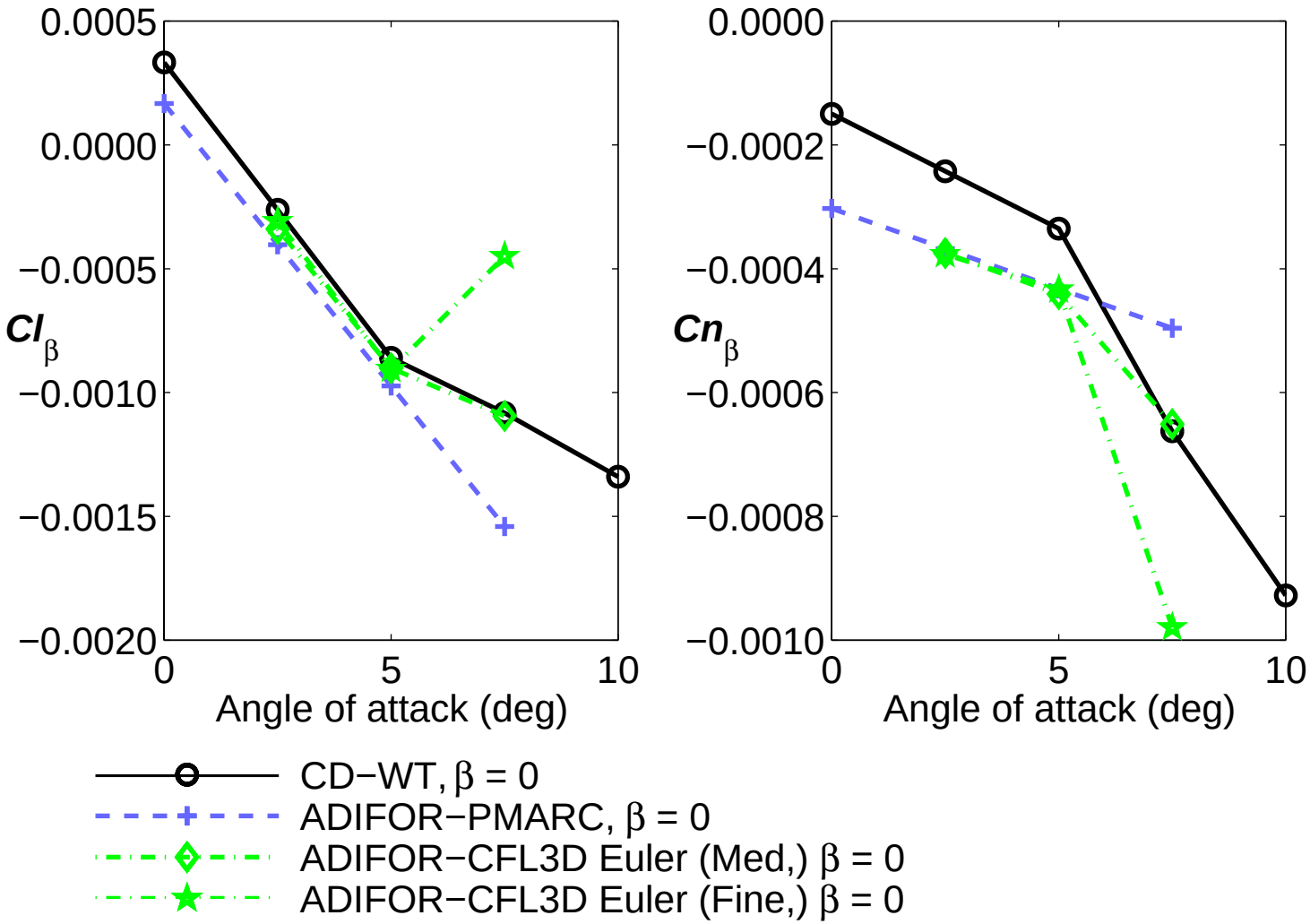
ADIFOR Results

Side force coefficient β derivative (M=0.60)



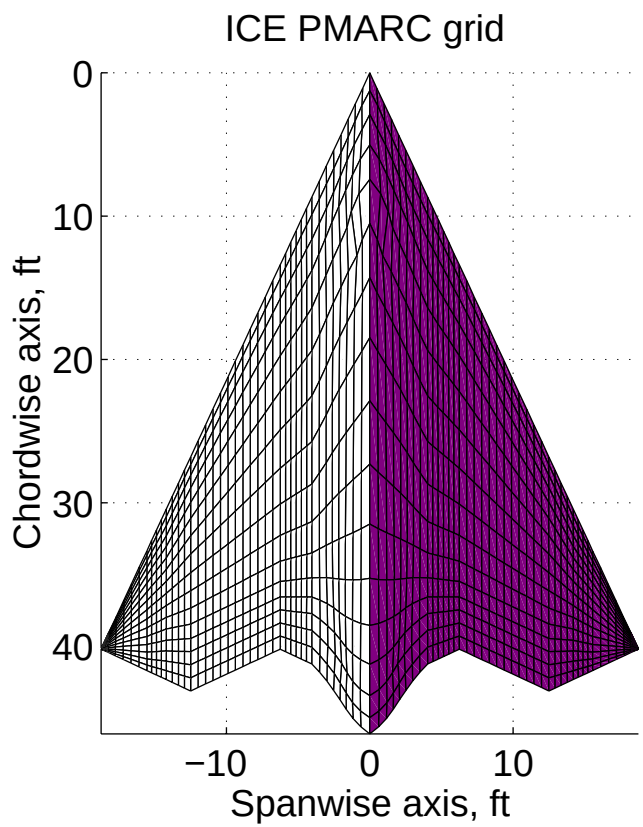
ADIFOR Results

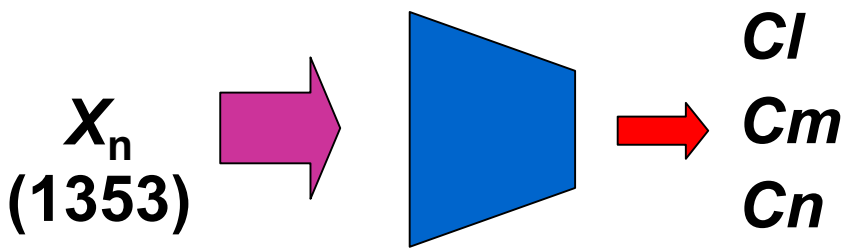
Lateral β derivatives (M=0.60)



ADJIFOR-PMARC Results
Control effectiveness derivatives

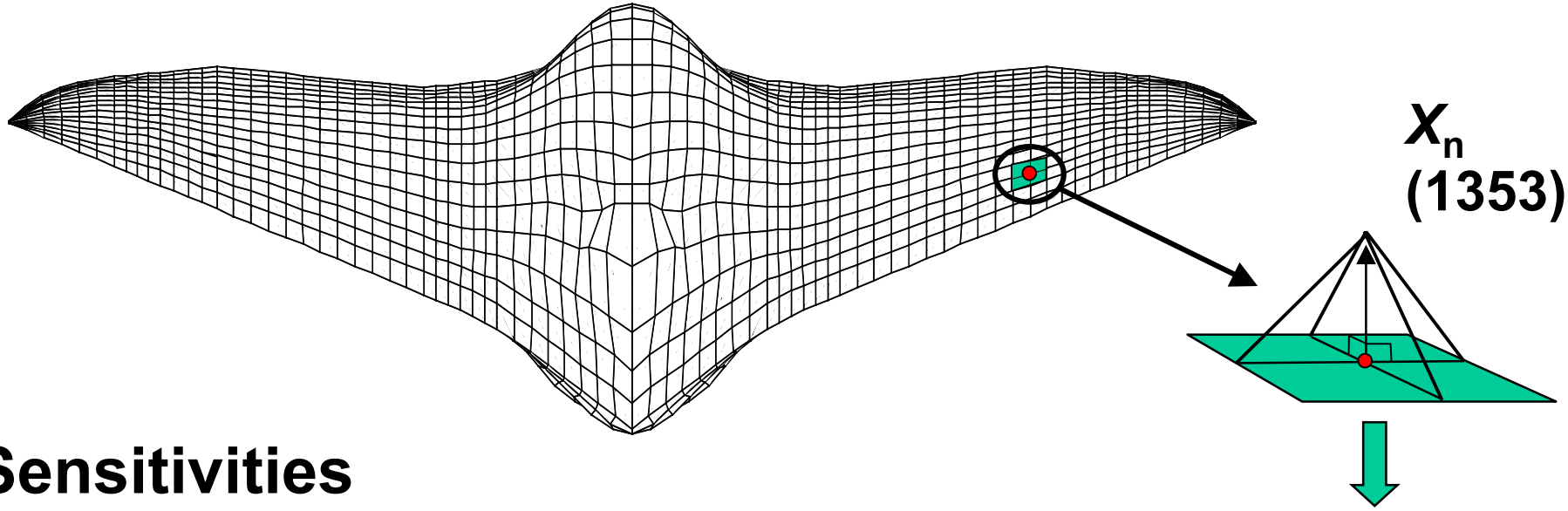
- Aircraft moment coefficient sensitivity to configuration shape changes





ADJIFOR-PMARC Results

Control effectiveness derivative definition



Sensitivities

- Pitch, Roll, and Yaw moment coefficient derivatives with respect to a displacement of the grid points normal to the surface
- Calculated for <u>each</u> of 1353 surface grid points
- Interpolated over the configuration

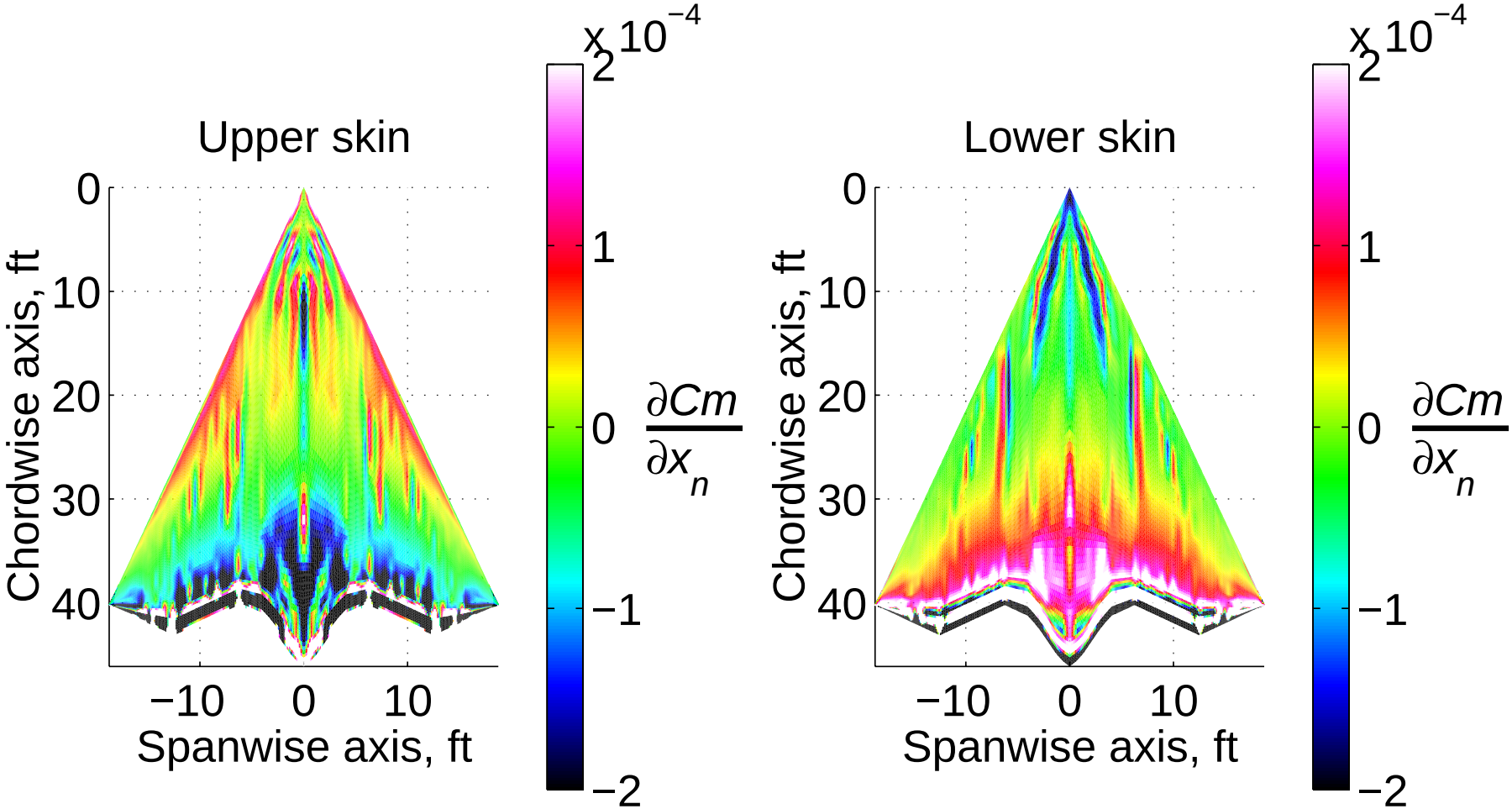
$$\left(\frac{\partial C_m}{\partial X_n}\right)$$

$$\left(\frac{\partial C_l}{\partial X_n}\right)$$

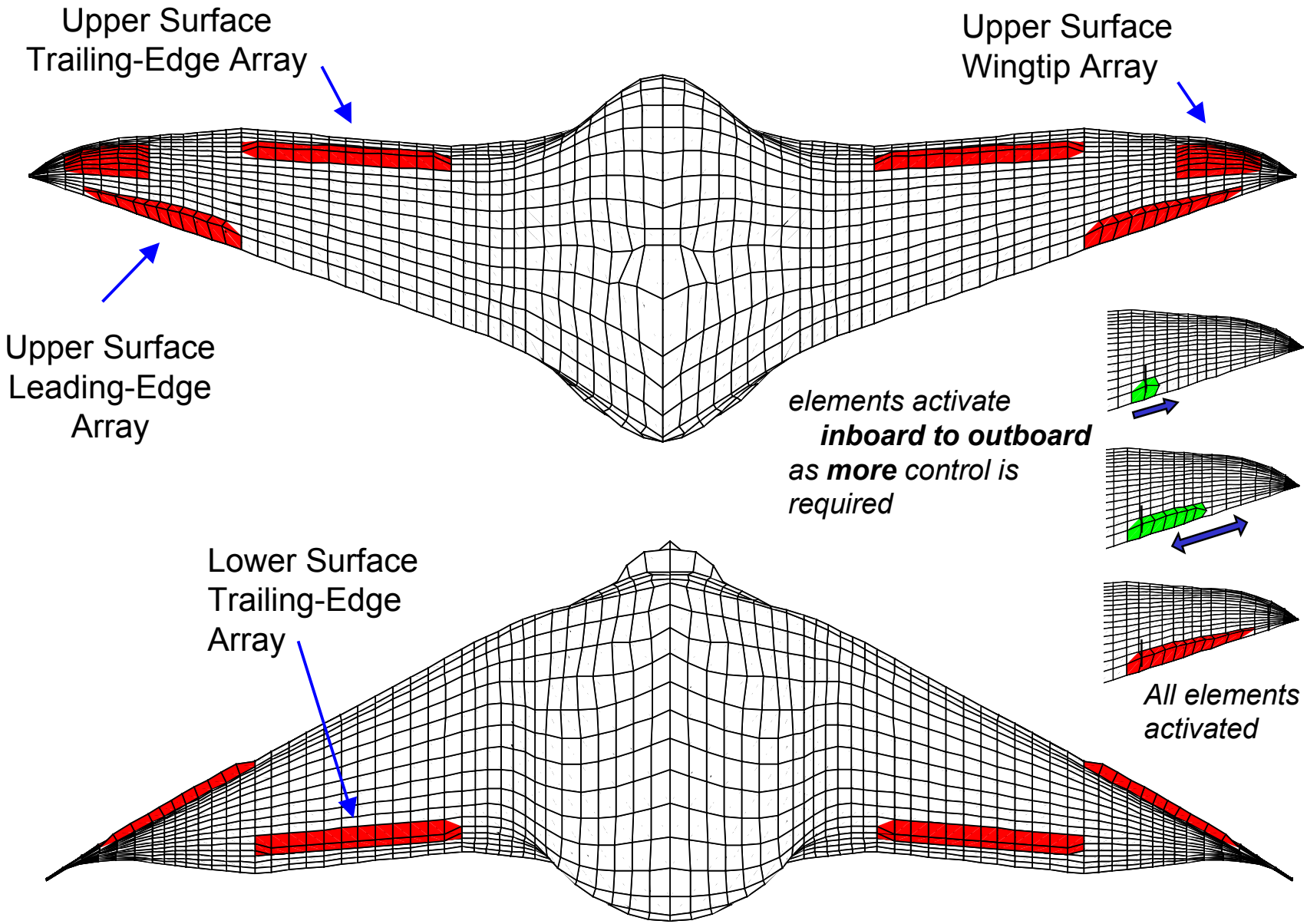
$$\left(\frac{\partial C_n}{\partial X_n}\right)$$

ADJIFOR-PMARC Results

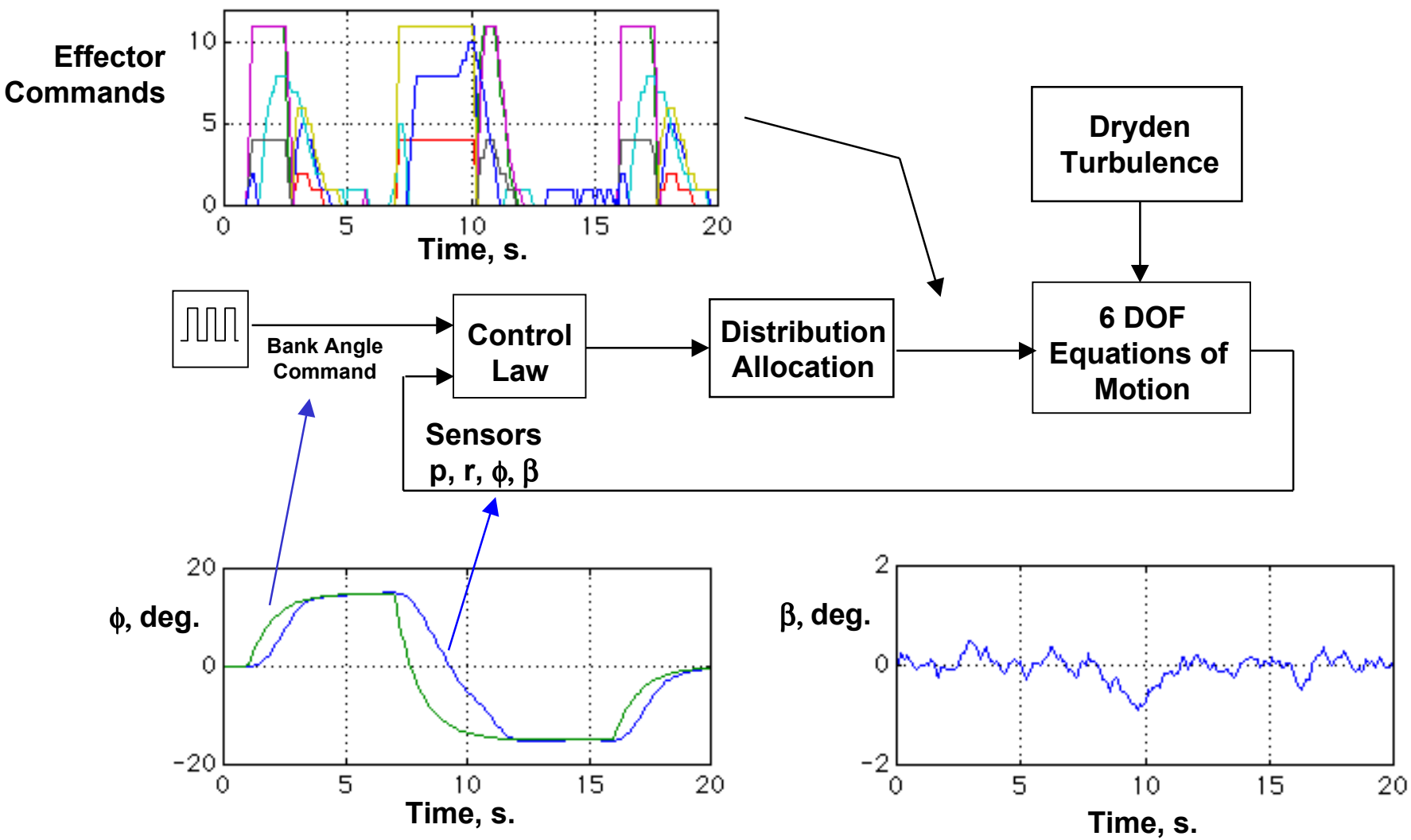
Pitch control effectiveness sensitivity contours (incompressible flow, α=4.39)



Most Promising Designs



ICE Simulation
– Mach 0.6, 15,000 ft. –



ADJIFOR-PMARC Timing / Memory

Code	Derivative	Disk	Time
PMARC	None	N/A	4 min.
CD-PMARC	1353 Normal Deflections	N/A	7.5 days (est.)
ADJIFOR-PMARC	1353 Normal Deflections	6000* Mbytes	20 min.

*Scratch file usage is expected to be reduced or eliminated with the final release of ADIFOR3.0 in Fall 1999

Conclusions

- CFD forces / moments agree well with wind tunnel (WT) data
- ADIFOR, ADJIFOR techniques have been demonstrated
  - Directly compute S&C derivatives from CFD codes
    - Compare with CD-CFD and CD-WT
    - Used in multidisciplinary effector / control law design
- Asymmetry in lateral WT - affects CD-WT derivatives
- ADIFOR-CFL3D may capture effects that are missed by taking a large step in WT data (4 deg beta)
- Panel method Euler turbulent N-S (cost & accuracy)
- Improved N-S grid, convergence studies, and lateral N-S
- ADJIFOR-CFD gives new capabilities (not possible in WT) at reasonable cost and significantly enhanced speed