Calculations of High-Lift Wing-Body Configuration with k-ω Model Variants

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Overall Objective

- To develop physics based improvements to RANS and multi-resolution PANS models for highly separated aerodynamic flows
  - Start from fundamental first principles
  - Develop all models from a single unified framework

Background and Motivation

- PANS proven in bluff body flows (FLUENT, FIRE, etc)
- Near-wall low Re PANS yet to be developed
  - Requires development physics based on low Re RANS models
- Many low Re RANS models are ad hoc and can not be directly applied to PANS
- Similar effort underway in Sweden (Peng et. al.)

Models Tested on Wing-Body for Workshop

- SA
- k-ε
- SST
- VLES
- RSM
- **k-ω**
  - Wilcox 1988 k-ω[§] (Baseline)
  - Wilcox 1988 k-ω with M1 Modification (M1)
  - Wilcox 1988 k-ω with M2 Modification (M2)
  - Wilcox 2006 k-ω[¶]

[§] Wilcox, D. C., ”Reassessment of the Scale-Determining Equation for Advanced Turbulence Models,” AIAA Journal, Vol.26, No. 11, 1988, pp. 1299-1310.

[¶] Wilcox, D. C., Turbulence Modeling for CFD, 3rd Ed., DCW Industries, 2006.

Outline

- Methodology of M1 and M2 Modifications
- Computational Setup
- Studies
  - P/ε Limiter Study
  - k-ω Model Variants Comparison with SA
  - Grid Convergence Study
  - Detailed Comparison of Baseline, M1, and SA Models
- Conclusions

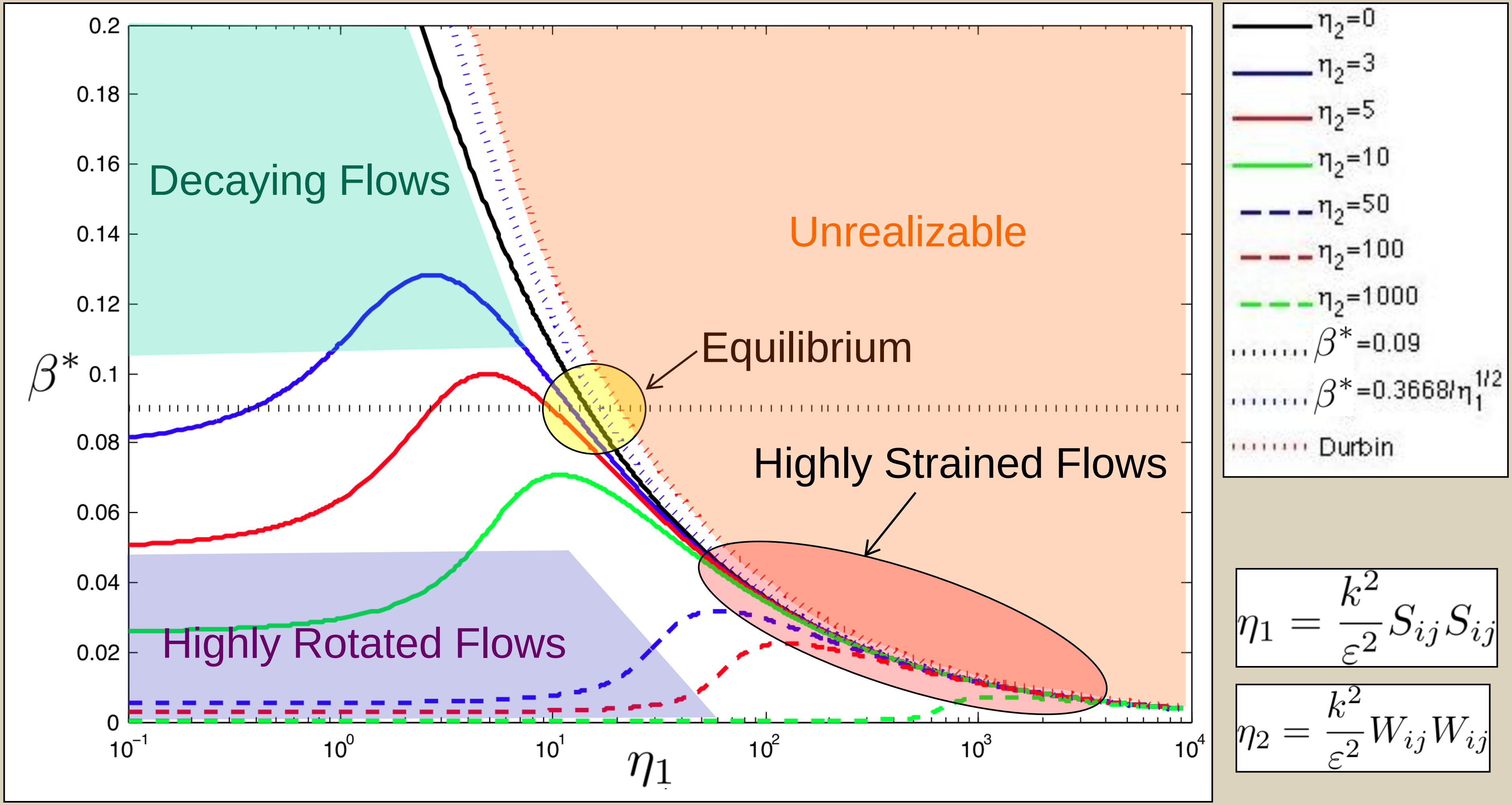
Standard Approach: Constant β* (C_μ)

- Constant β* valid when
  - Turbulence is near equilibrium

Not Applicable When

- Flow is very rapidly strained
  - S>>ω
  - Mean strain >> fluctuating strain
  - Turbulence is elastic rather than viscous
  - $\beta^* = \beta^*(S,\omega)$
- Rotation Dominated Flows
  - W>>S
  - $\beta^* = \beta^*(S,W,\omega)$

General β^* Behavior



$$\eta_1 = \frac{k^2}{\varepsilon^2} S_{ij} S_{ij}$$

$$\eta_2 = \frac{k^2}{\varepsilon^2} W_{ij} W_{ij}$$

ARSM Based Variable β* Model

Full ARSM: $b_{ij} = G_1 S^*_{ij} + G_2 (S^*_{ij} W^*_{kj} - W^*_{ik} S^*_{kj}) + G_3 \left(S^*_{ik} S^*_{kj} - \frac{1}{3} S^*_{mn} S^*_{mn} \delta_{ij} \right)$

Linear Truncated ARSM: $b_{ij} = G_1 S^*_{ij}$

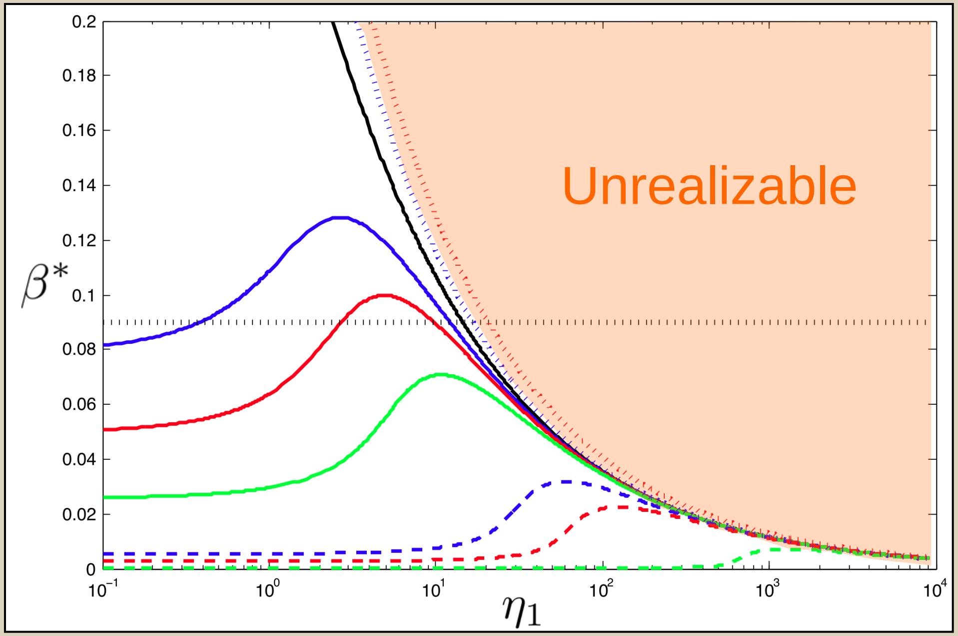
$$b_{ij} = G_1 S^*_{ij} \quad \Longrightarrow \quad \overline{u_i u_j} = G_1 \frac{k^2}{\varepsilon} S_{ij} + \frac{2}{3} k \delta_{ij} \quad \Longrightarrow \quad \overline{u_i u_j} = -C_\mu \frac{k^2}{\varepsilon} S_{ij} + \frac{2}{3} k \delta_{ij}$$

$$\Longrightarrow \quad -C_\mu = -\beta^* = G_1 = \begin{cases} \frac{L_1^0 L_2}{(L_1^0)^2 + \eta_2 (L_4)^2} \\ \frac{L_1^0 L_2}{(L_0)^2 \frac{2}{3} \eta_1 (L_3)^2 + 2\eta_2 (L_4)^2} \\ -\frac{p}{3} + \left(-\frac{b}{2} + \sqrt{D} \right)^{\frac{1}{3}} + \left(-\frac{b}{2} - \sqrt{D} \right)^{\frac{1}{3}} \\ -\frac{p}{3} + 2\sqrt{\frac{-a}{3}} \cos(\frac{\theta}{3}) \\ -\frac{p}{3} + 2\sqrt{\frac{-a}{3}} \cos(\frac{\theta}{3} + \frac{2\pi}{3}) \end{cases}$$

Girimaji, S.S., ”Fully explicit and self-consistent algebraic Reynolds stress model,” Theoretical and Computational FluidDynamics, Vol. 8, No. 6, 1996, pp. 387-402.

M2 Model

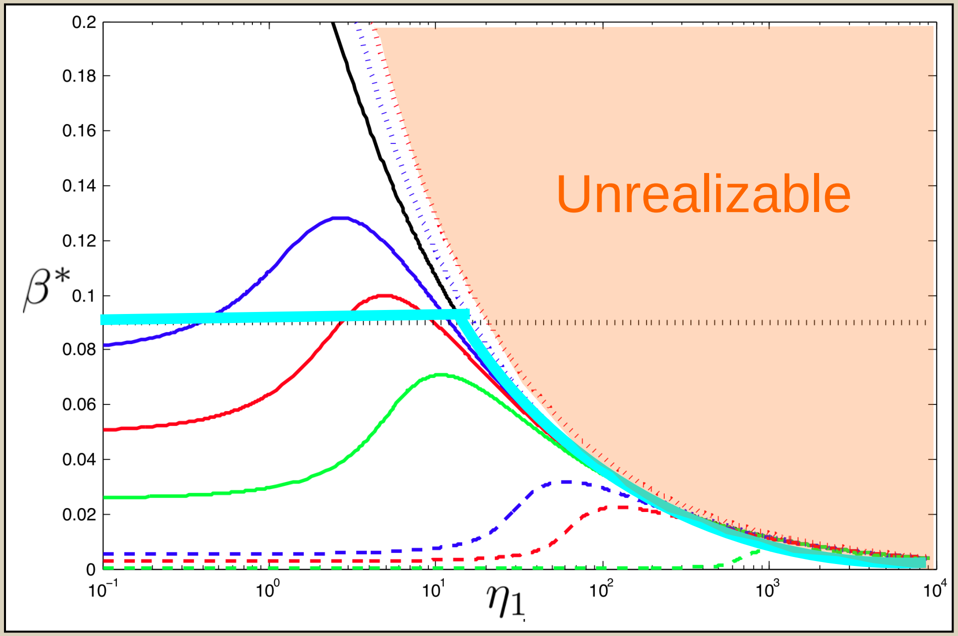
- M2: Valid for all strain rates and rotation rates
  - Linear coefficient from ARSM, $\beta^*=\beta^*(W_{ij},S_{ij})$



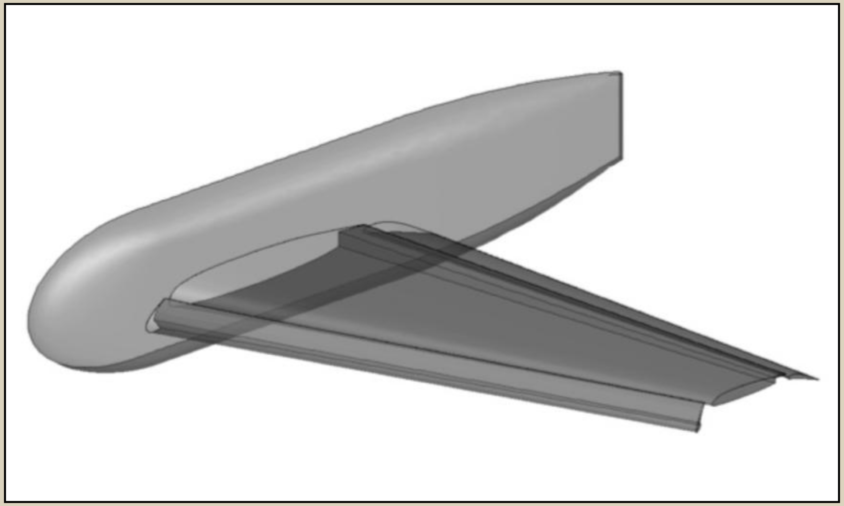
$$-\beta^* = G_1 = \begin{cases} \frac{L_1^0 L_2}{(L_1^0)^2+\eta_2(L_4)^2} \\ \frac{L_1^0 L_2}{(L_0)^2 \frac{2}{3}\eta_1(L_3)^2+2\eta_2(L_4)^2} \\ -\frac{p}{3}+\left(-\frac{b}{2}+\sqrt{D}\right)^{\frac{1}{3}}+\left(-\frac{b}{2}-\sqrt{D}\right)^{\frac{1}{3}} \\ -\frac{p}{3}+2\sqrt{\frac{-a}{3}}\cos(\frac{\theta}{3}) \\ -\frac{p}{3}+2\sqrt{\frac{-a}{3}}\cos(\frac{\theta}{3}+\frac{2\pi}{3}) \end{cases}$$

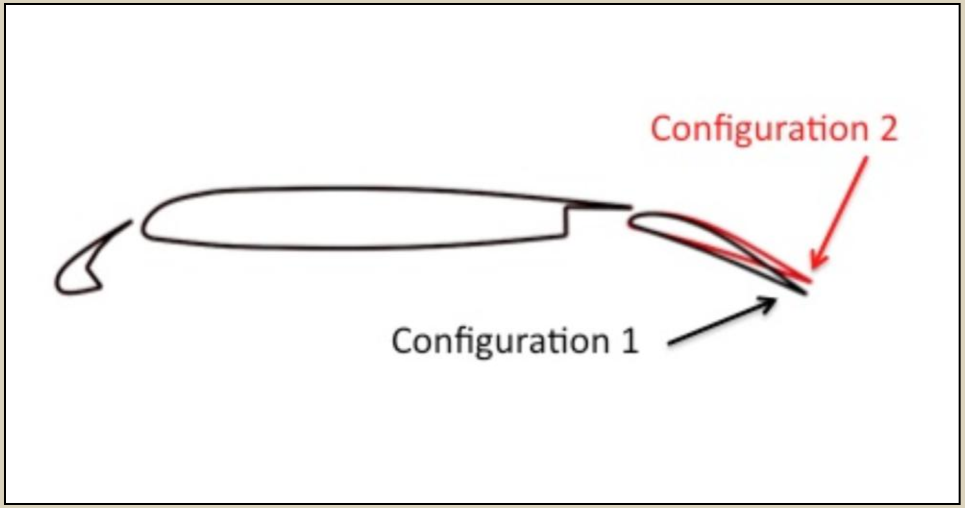
M1 Model

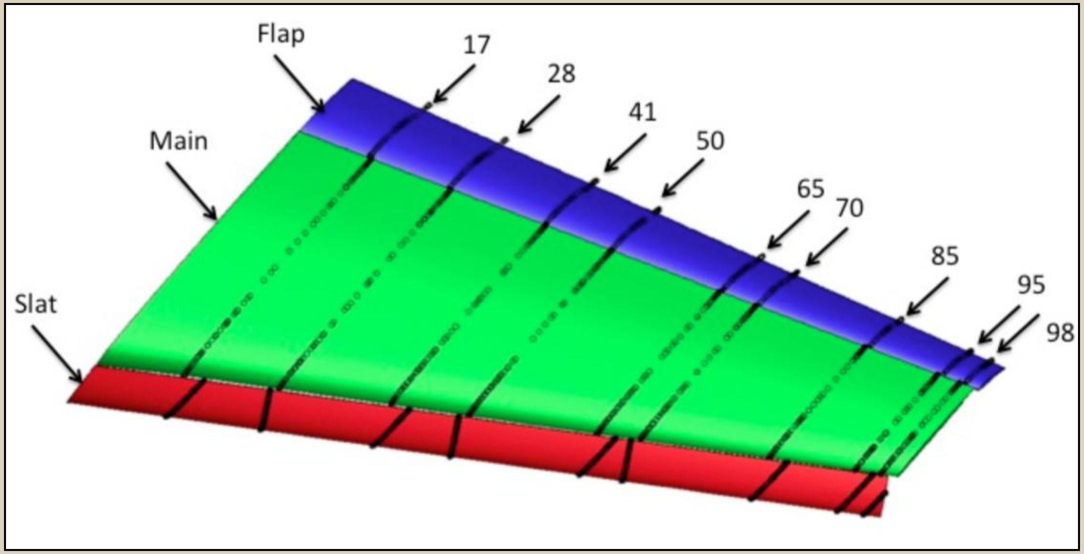
- M1: Valid for all strain rates
  - $Sk/\varepsilon < 5 \rightarrow \beta^*=0.09$
  - $Sk/\varepsilon > 5 \rightarrow$ ARSM Values
- $$\beta^* = min\left[0.3668\left(\frac{0.09\omega}{S}\right), 0.09\right]$$
- Similar to Durbin's realizability model



Computational Setup: Wing Body Geometry







Configuration	Slat	Flap
1	30 deg	25 deg
2	30 deg	20 deg

Computational Setup

- USM3D
  - tetrahedral time accurate solver
  - all simulations are steady state
- Grids
  - Coarse Grid: 7,237,190
  - Medium Grid: 21,743,354
  - Fine Grid: 62,644,381
- Models
  - Wicox's 1988 k-ω
  - Wilcox's 1988 k-ω with M1 modification
  - Wilcox's 1988 k-ω with M2 modification
  - Wilcox's 2006 k-ω
  - Spalart Almaras (SA)

Computational Setup

- Two Configurations Tested
  - Configuration 1
    - Slat 30 degree deflection
    - Flap 25 degree deflection
  - Configuration 2
    - Slat 30 degree deflection
    - Flap 25 degree deflection
- Angle of attacks: 6, 13, 18, 21, 28, 32, 34, 37
- M=0.2
- Re=4.3×10^6

Results

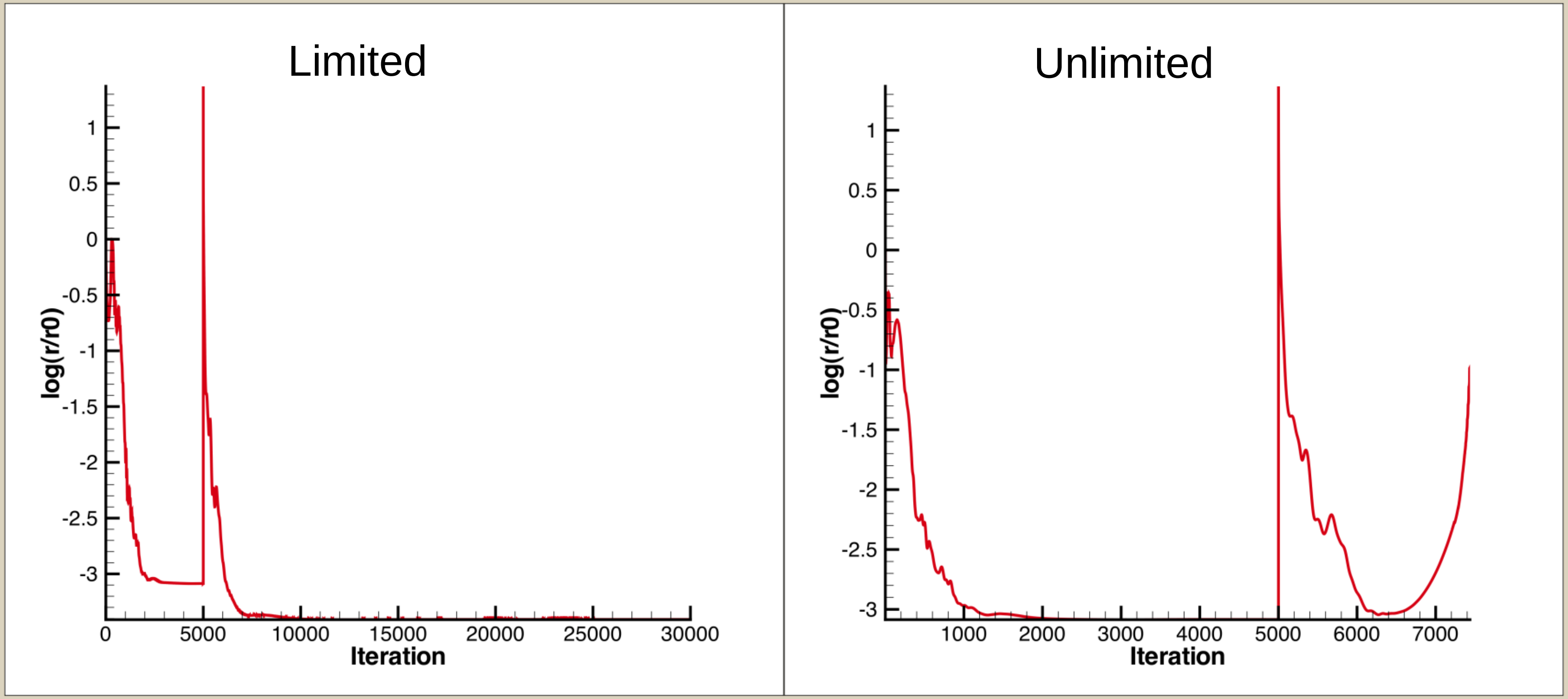
- **Study 1:** P/ε Limiter Study
  - Unlimited and Limit=20
- **Study 2:** Model Comparison Study
  - k-ω Model Variants and SA
- **Study 3:** Grid Convergence Study of Baseline and M1
- **Study 4:** Direct Comparison of Baseline, M1, and SA

Study 1: P/ε Limiter

k-ω Model Variants

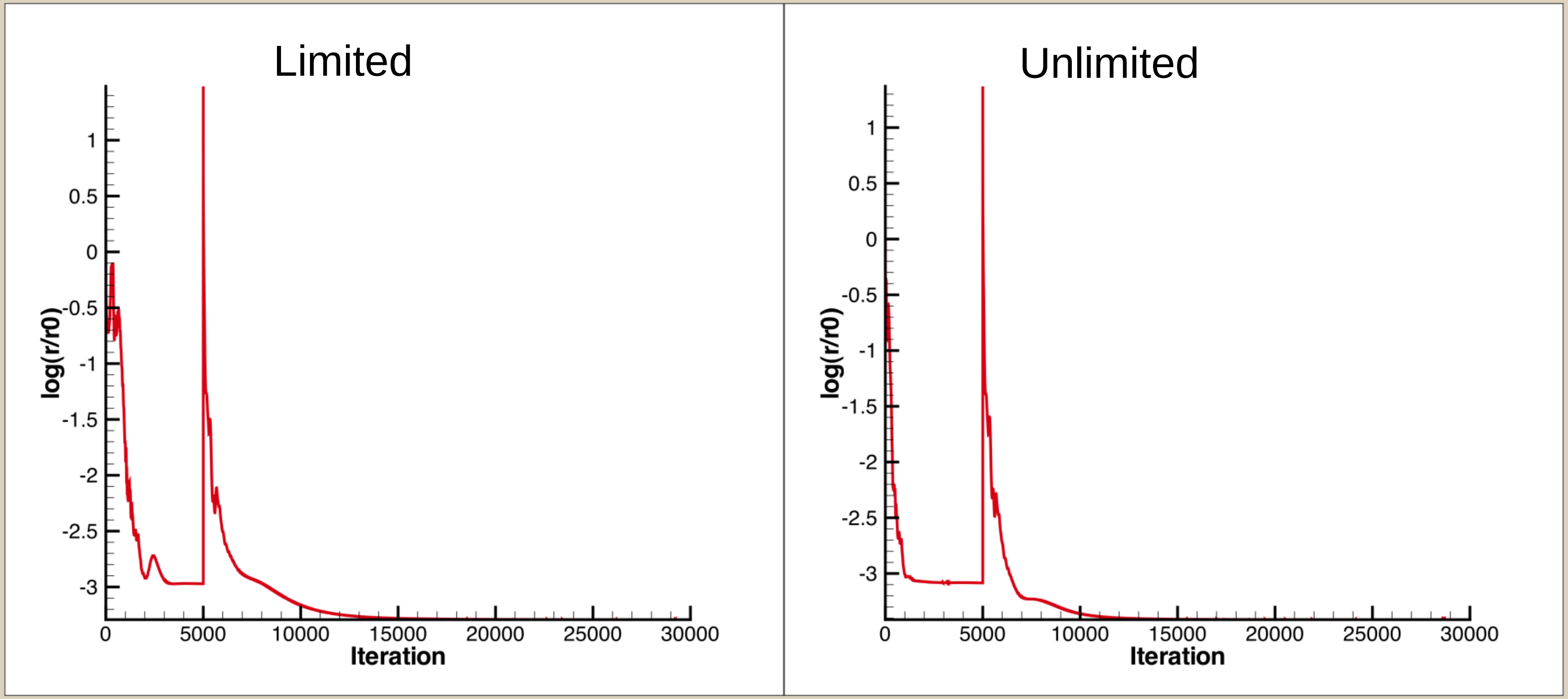
AOA 13 Configuration 1

Baseline



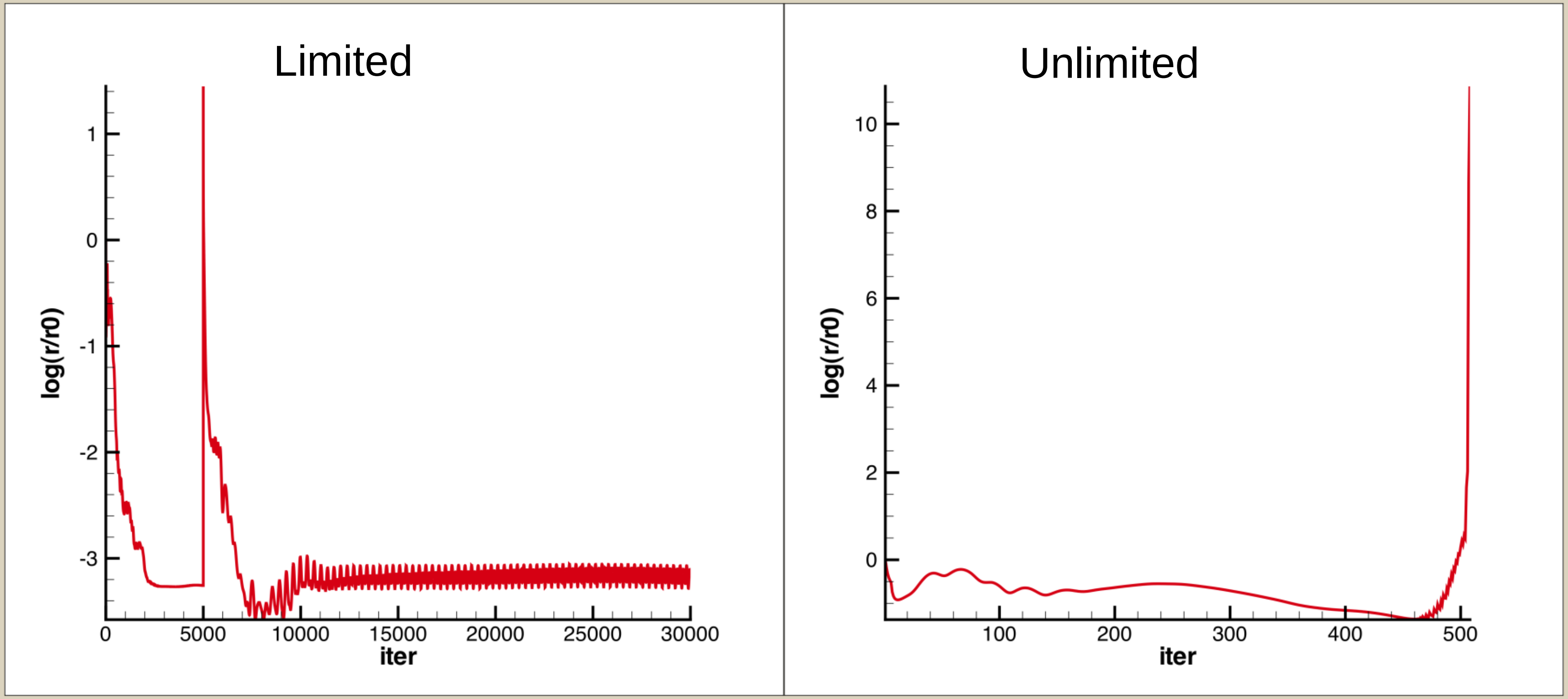
Unlimited P/ε has significant effect on convergence.

M1



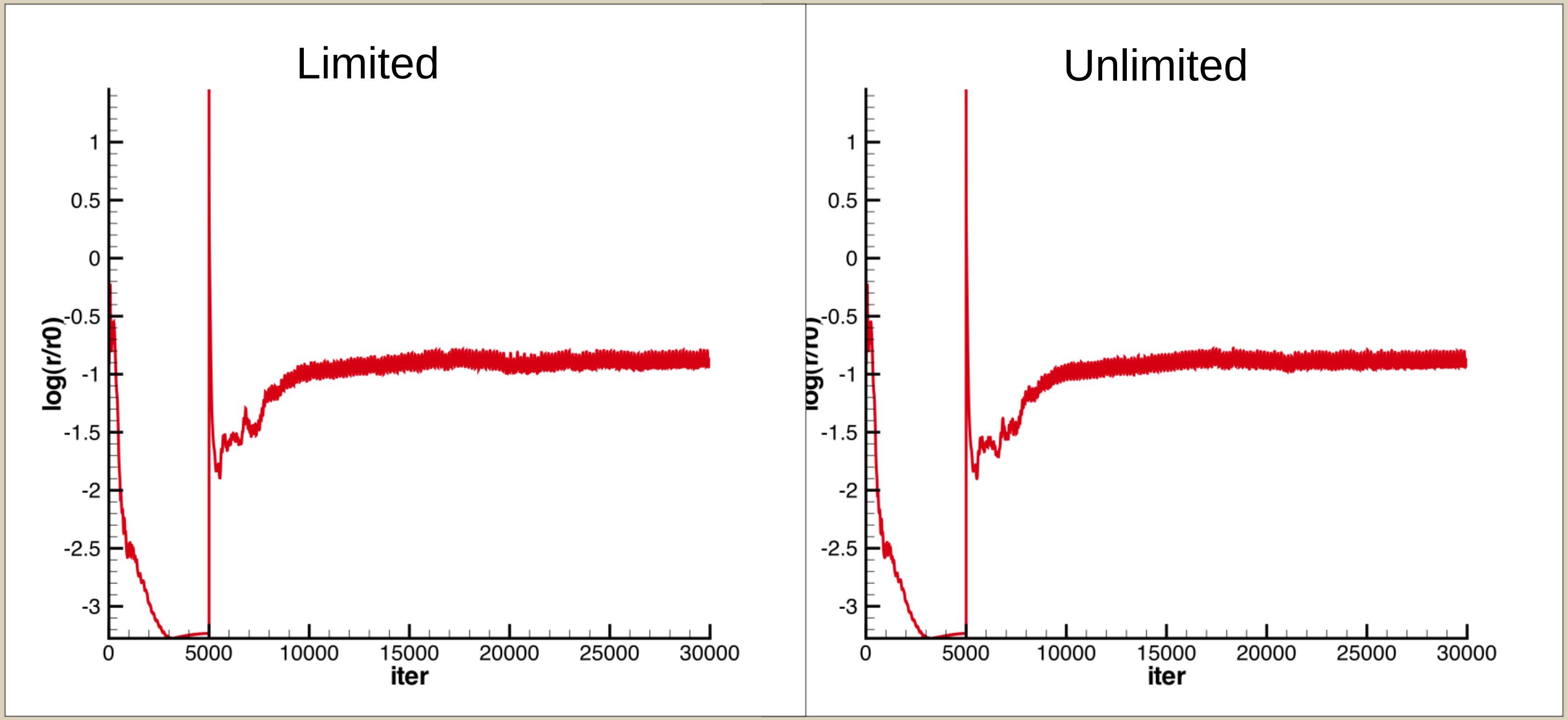
M1 is insensitive to P/ε limiter.

M2



Outstanding implementation issues are observed with M2.

Wilcox 2006

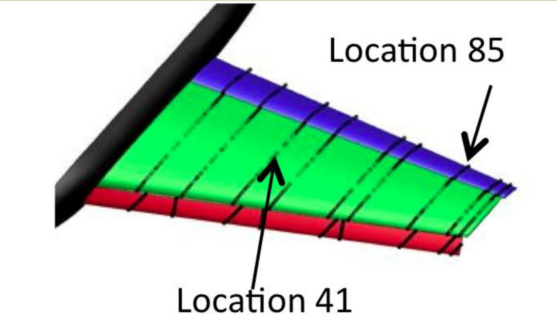


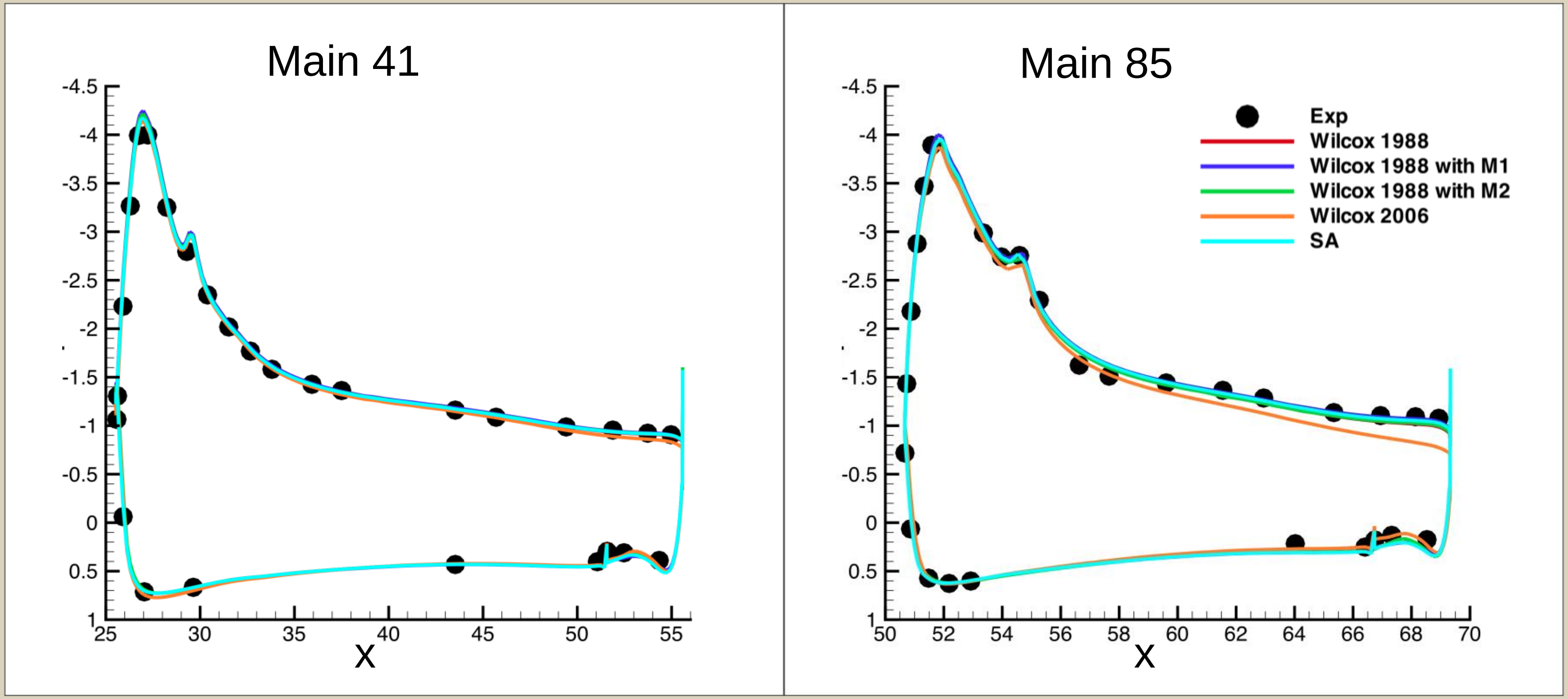
Unlimited P/ε has insignificant effect on convergence.

Study 2: Model Comparison Studies

C_p Distribution at AOA 13
Configuration 1

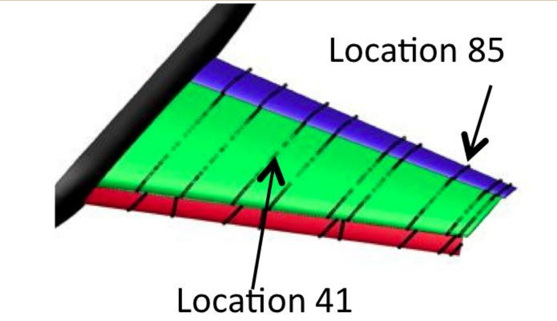
AOA 13

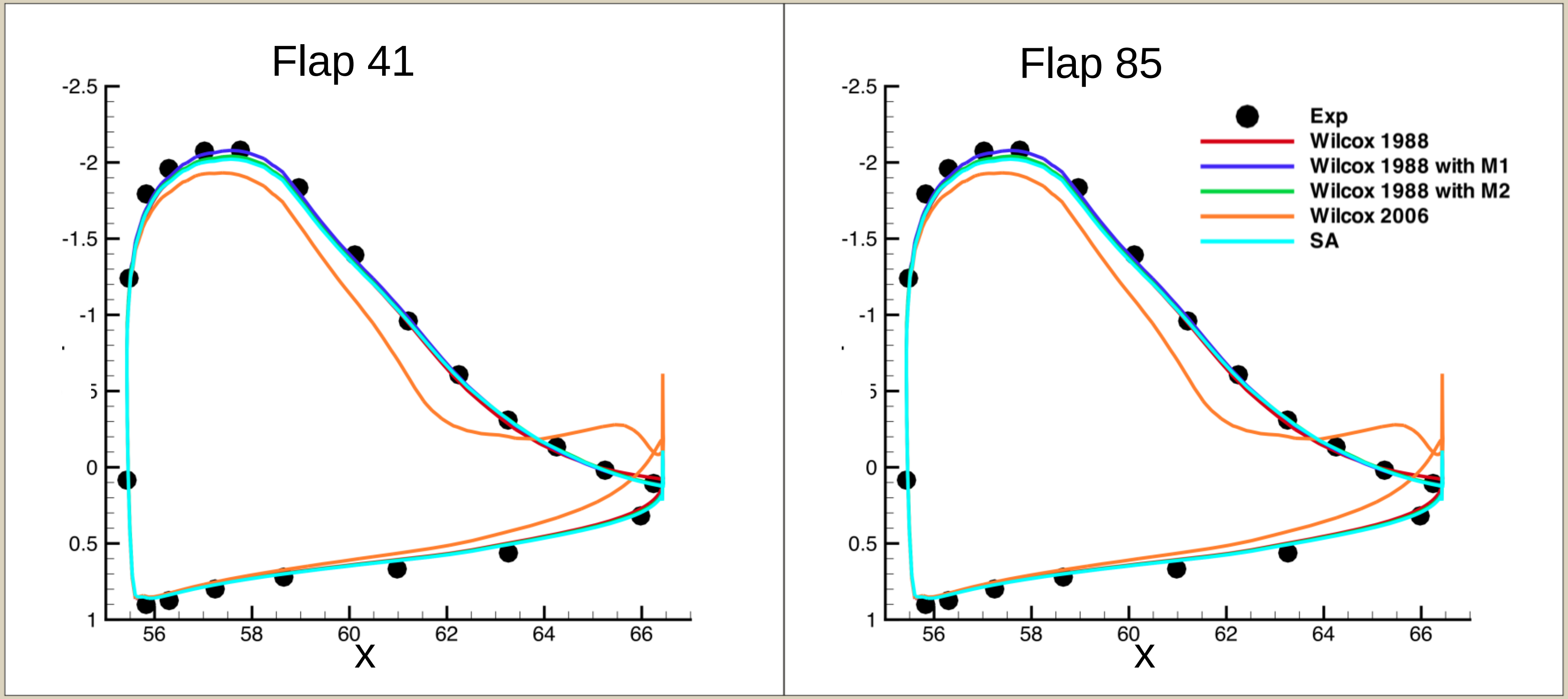




All models are comparable with Wilcox 2006 performing slightly worse.

AOA 13





Wilcox 2006 performs poorly.
M2 needs to be further investigated.

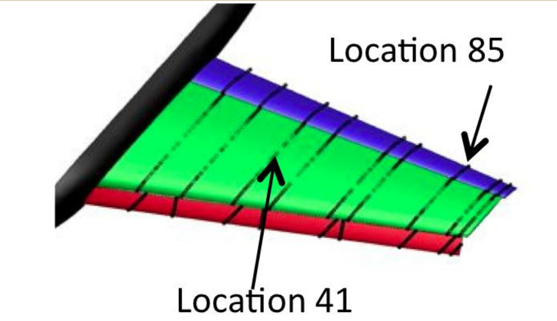
Study 3: Grid Convergence for Baseline and M1

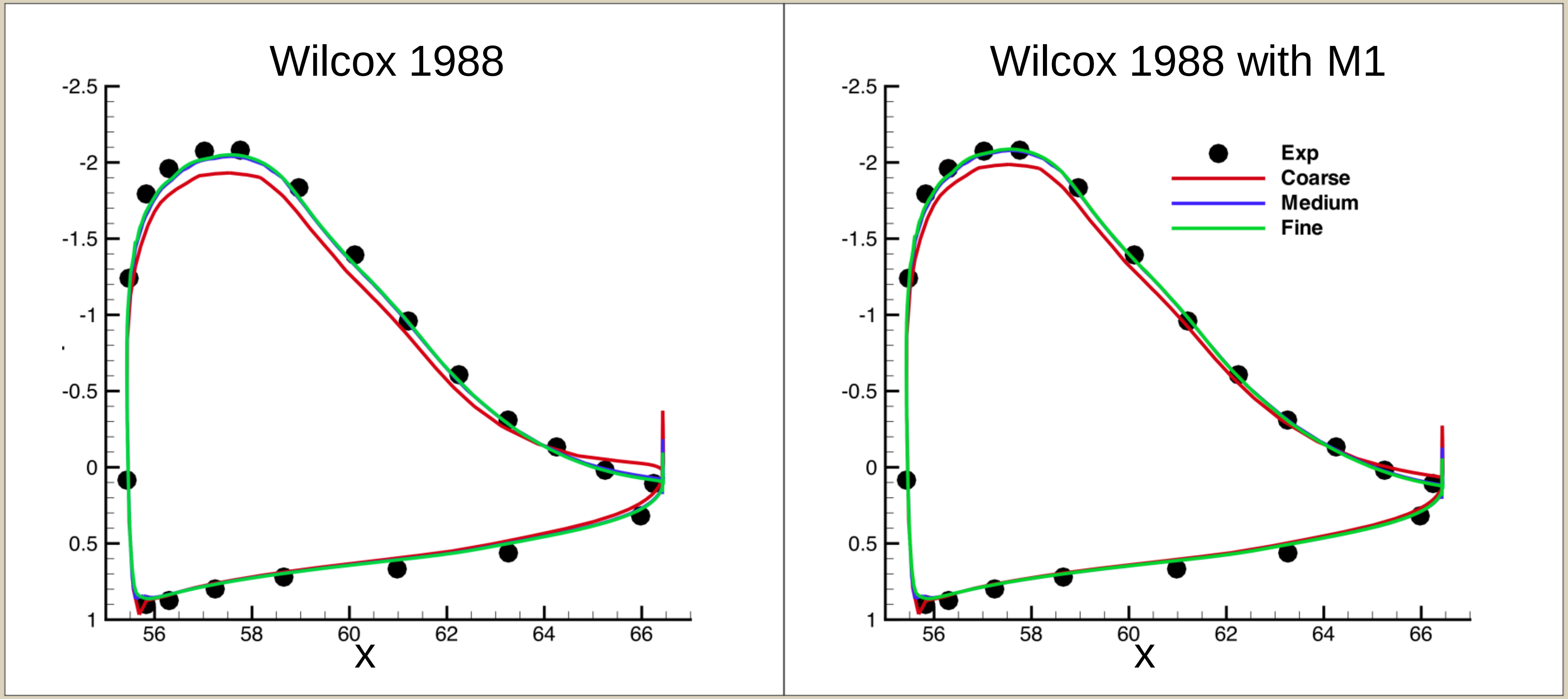
C_p Distribution at AOA 13

Configuration 1

Flap 41

AOA = 13 degrees

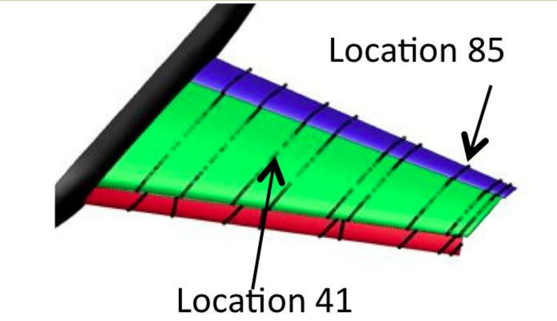


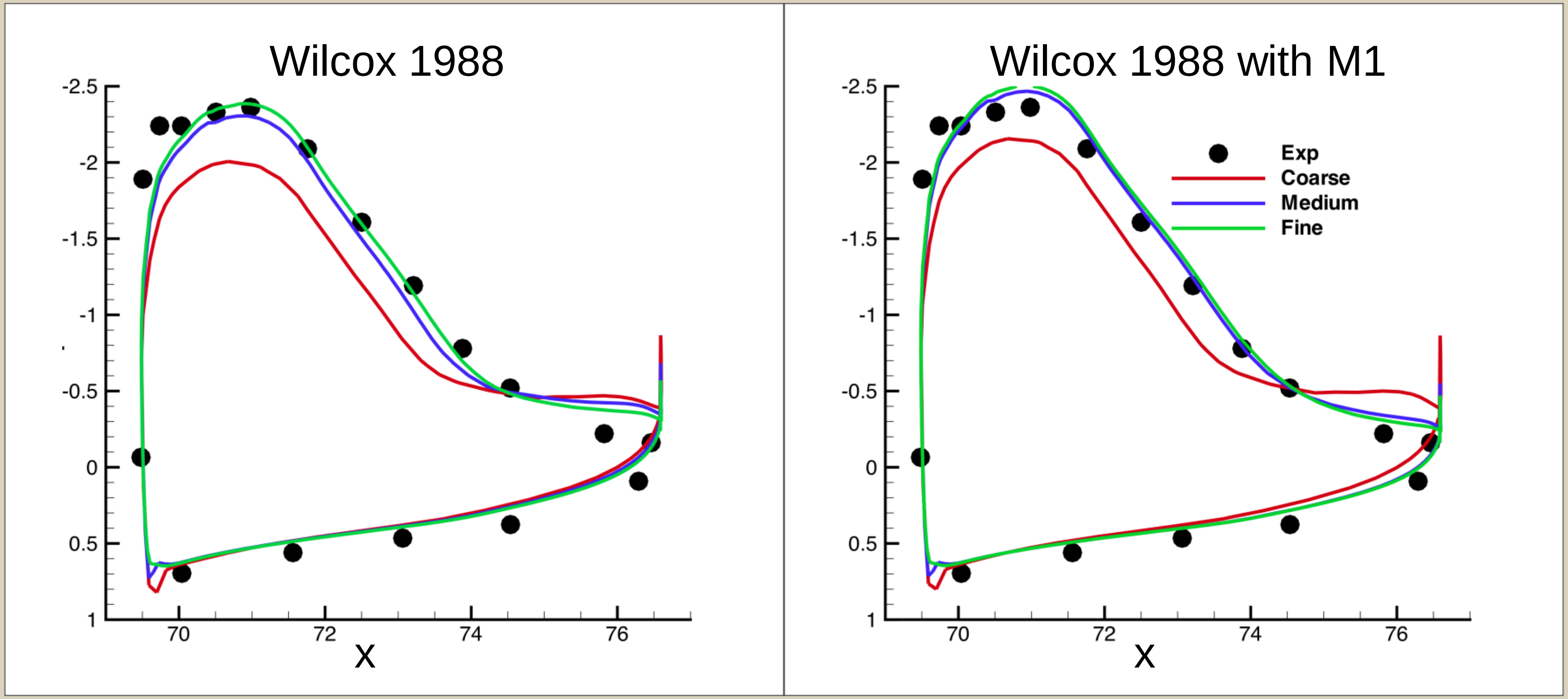


Grids convergence for each model at AOA 13.

Flap 85

AOA = 13 degrees




Wilcox 1988

Wilcox 1988 with M1

Convergence between medium and fine grids is better for M1.

Study 4: Comparisons of Baseline, M1, and SA

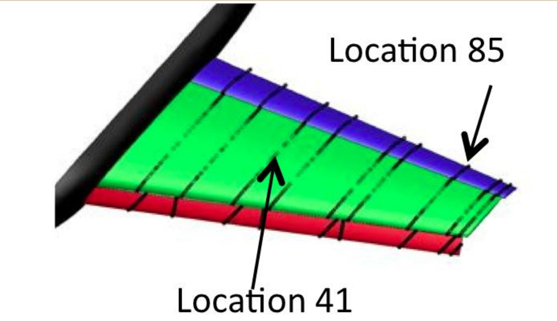
C_p Distribution at AOA 13 & 28

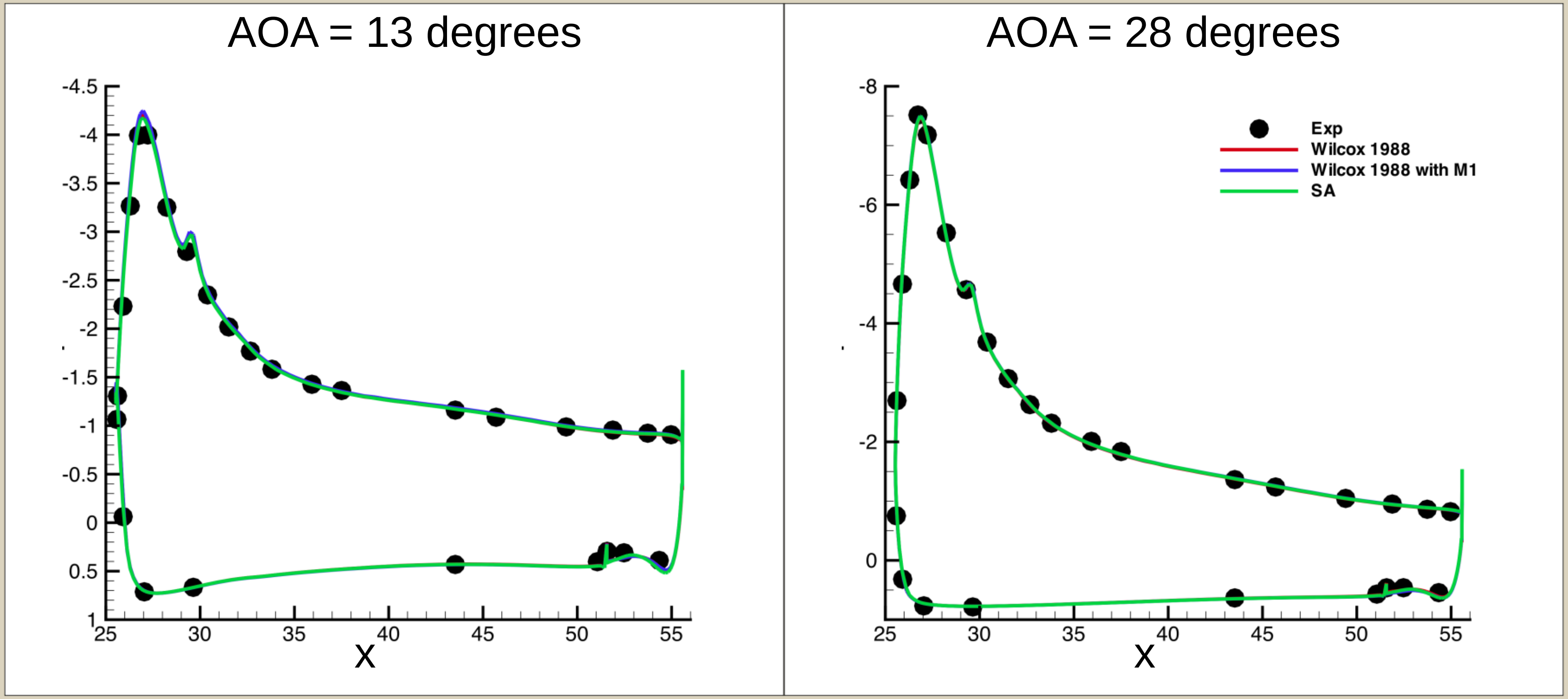
Configuration 1

Force and Moment Plots

Configurations 1 & 2

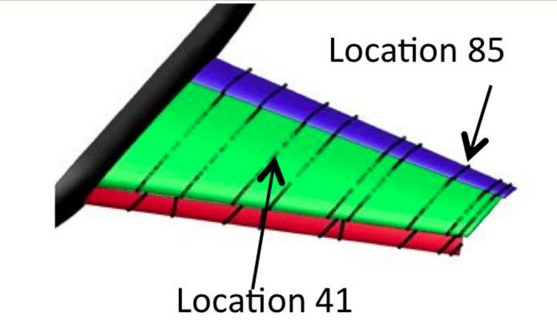
Main 41

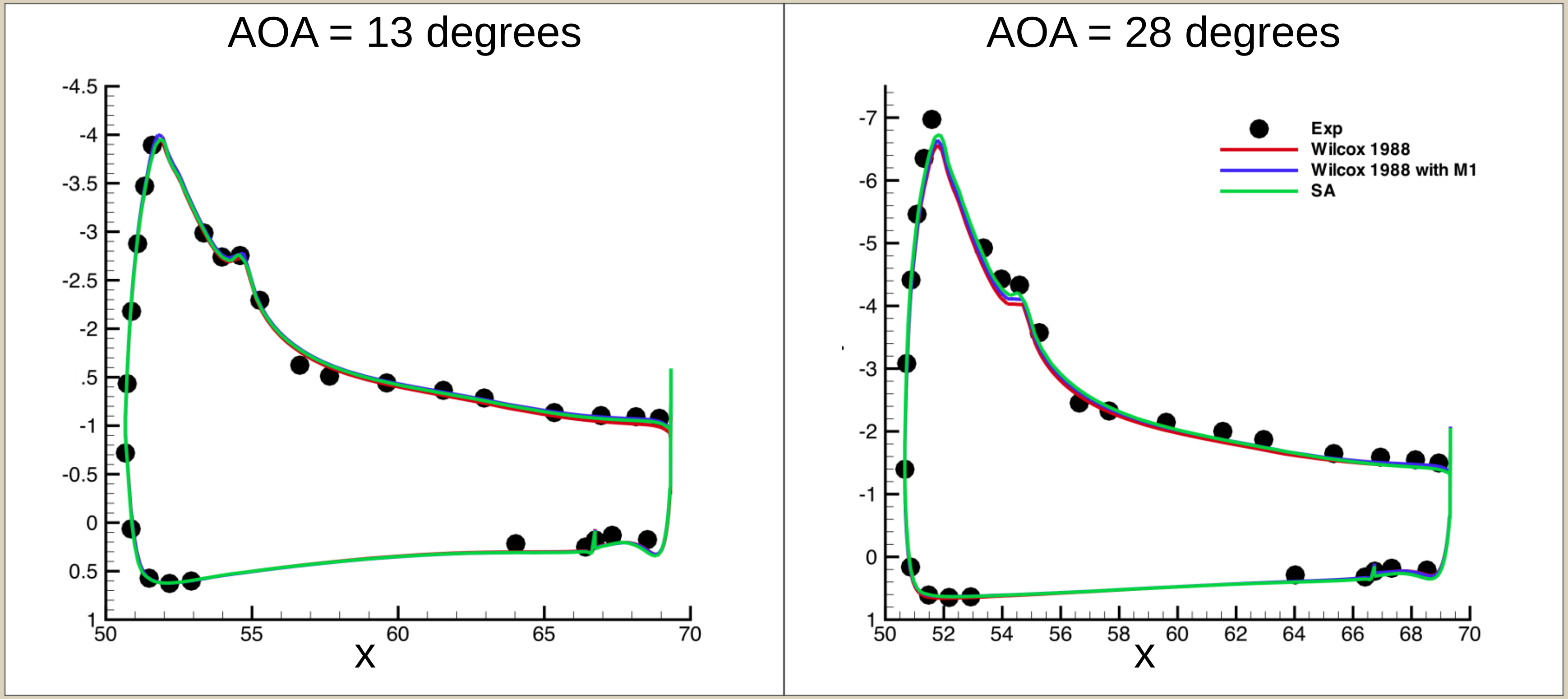




Models perform equally well.

Main 85

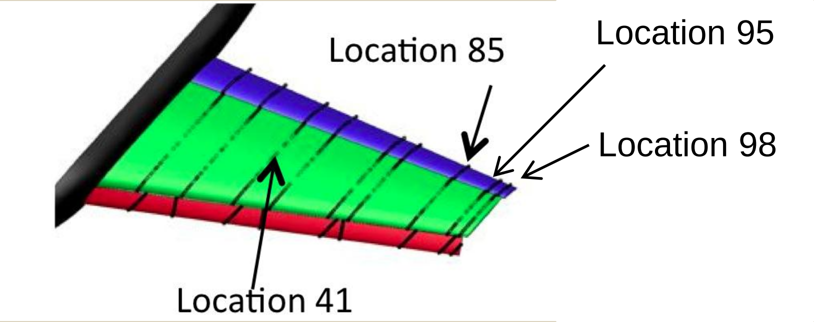


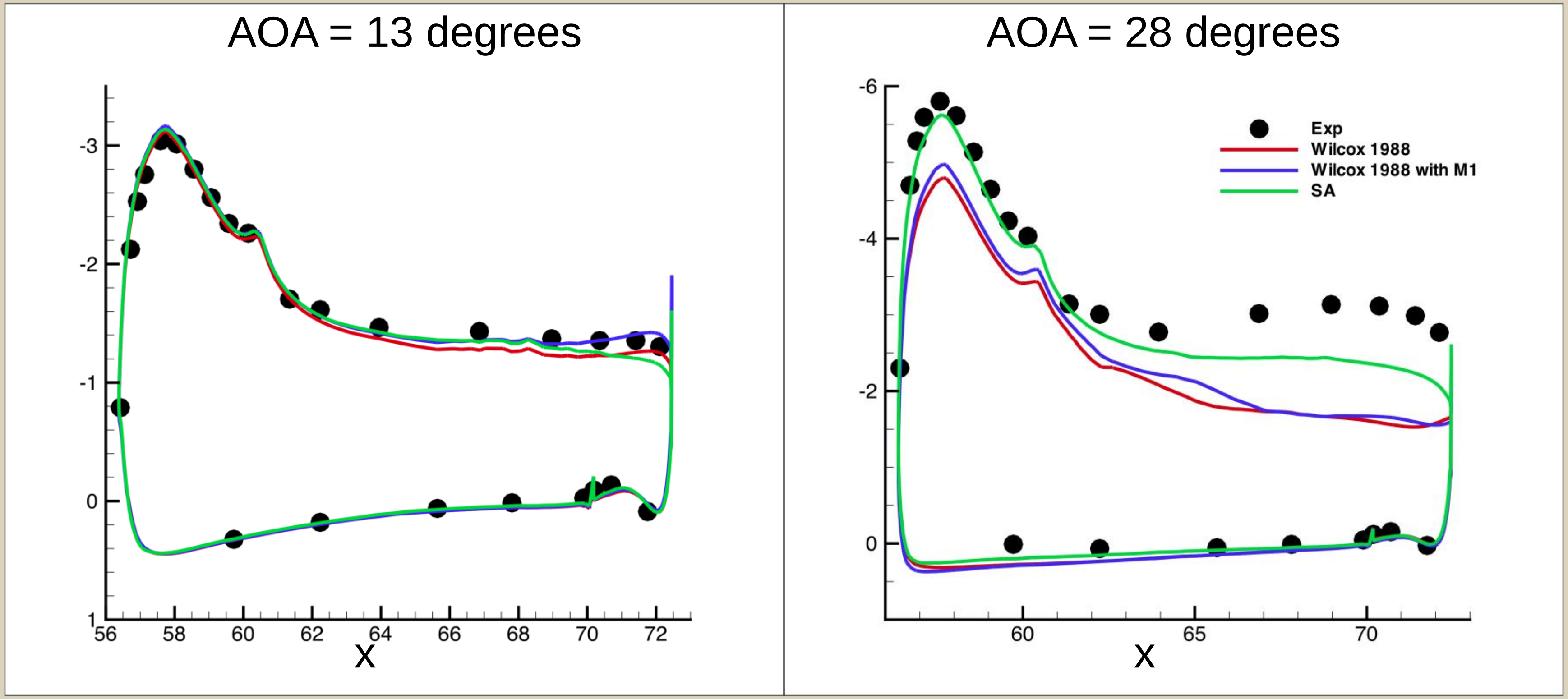

AOA = 13 degrees

AOA = 28 degrees

Models perform equally well.

Main 95



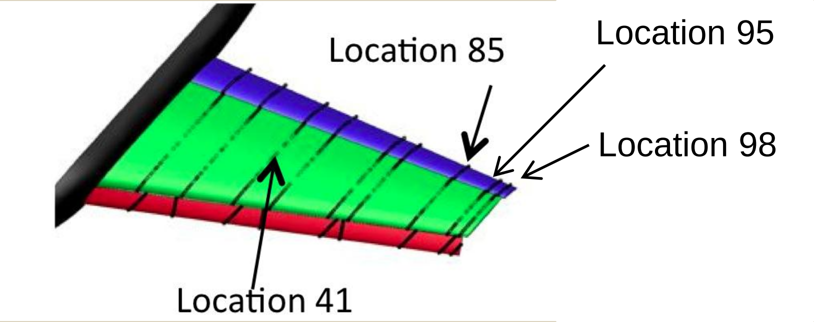

AOA = 13 degrees

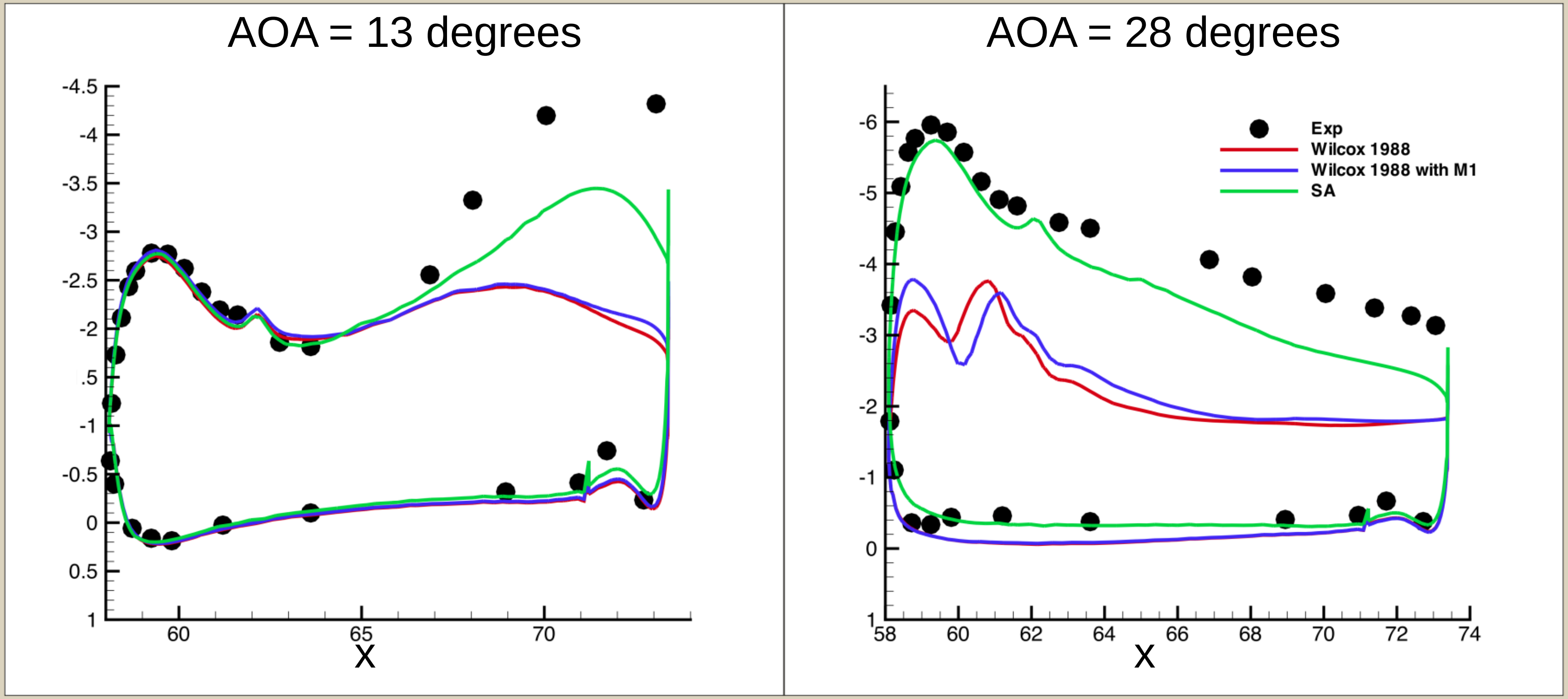
AOA = 28 degrees

SA performs best.

M1 performs marginally better than Wilcox 1988.

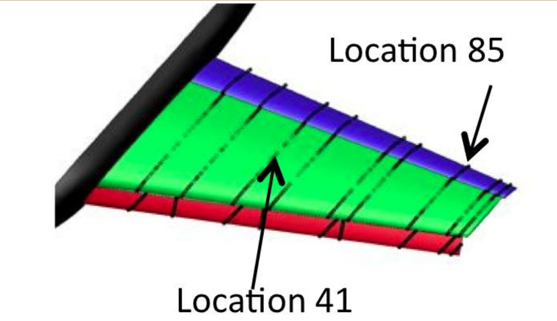
Main 98

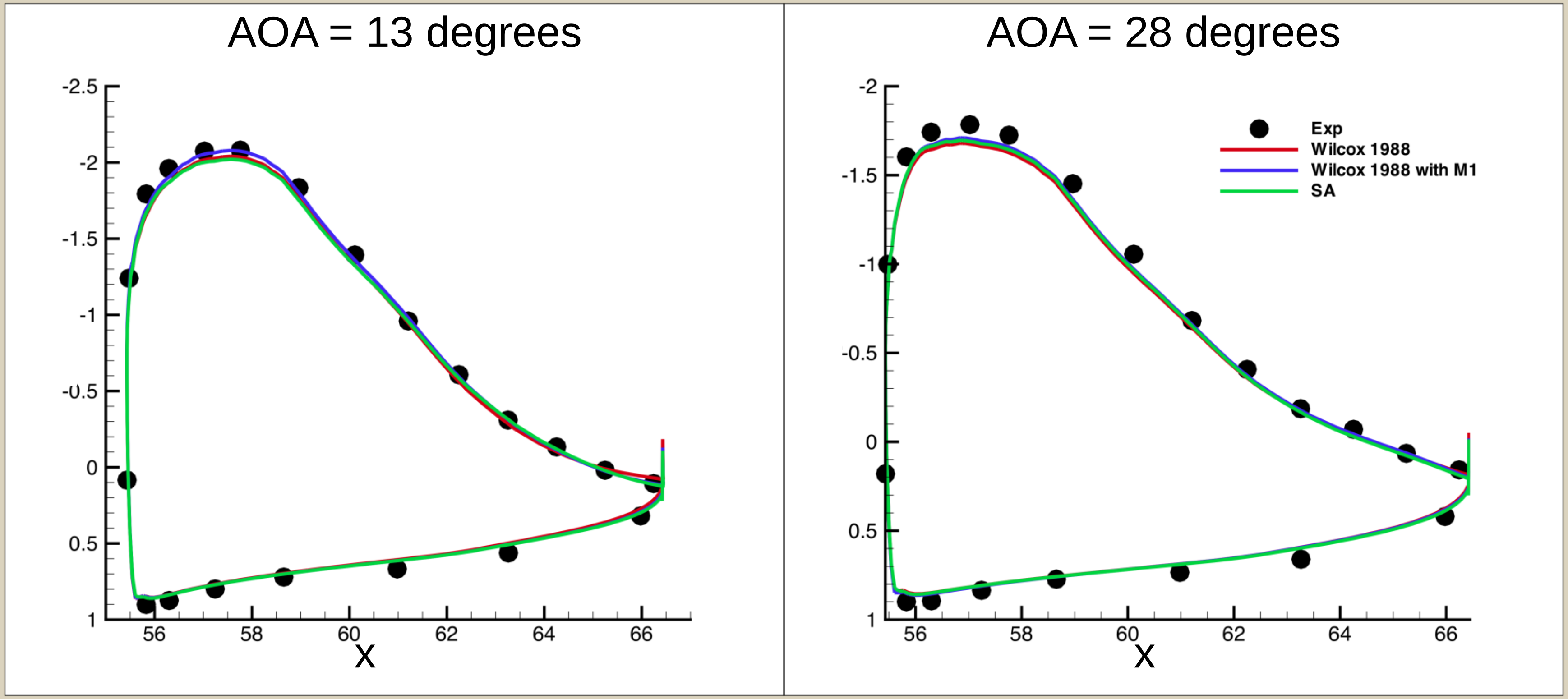




SA performs best.

Flap 41

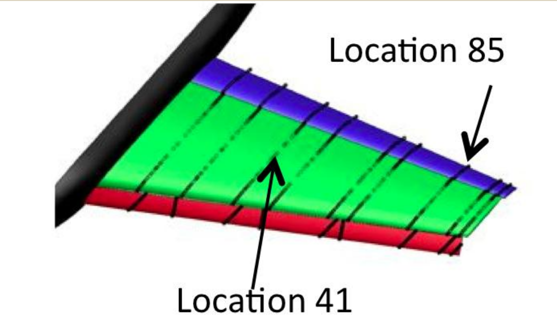


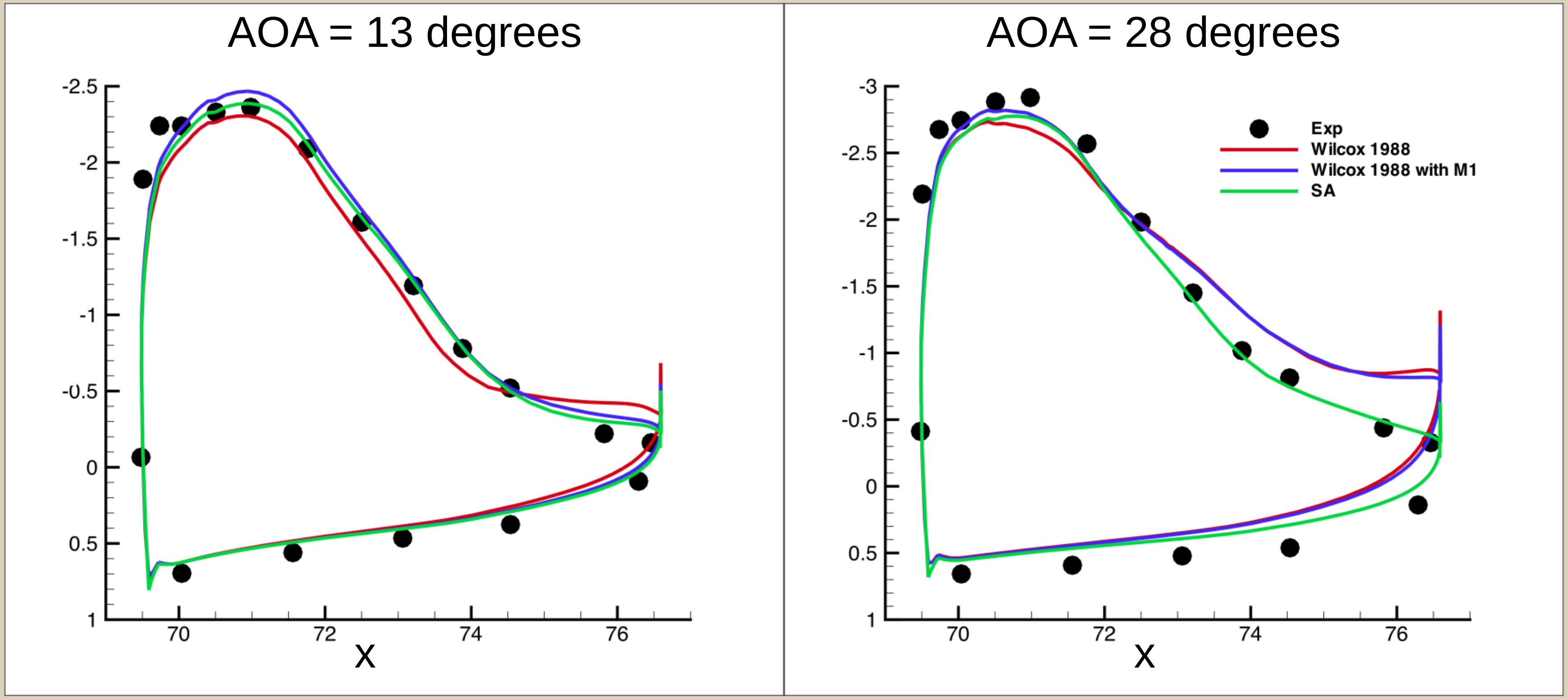

AOA = 13 degrees

AOA = 28 degrees

Models perform equally well.

Flap 85

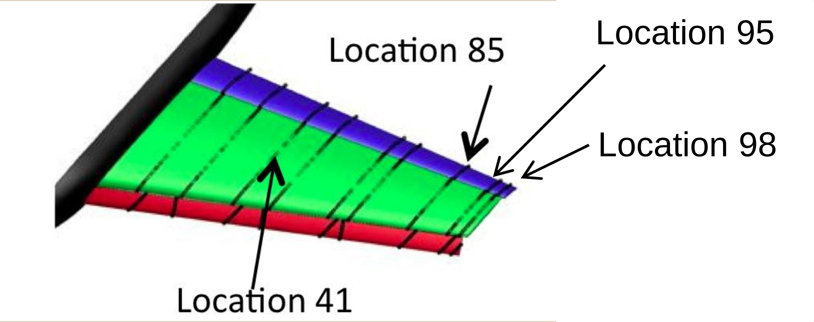


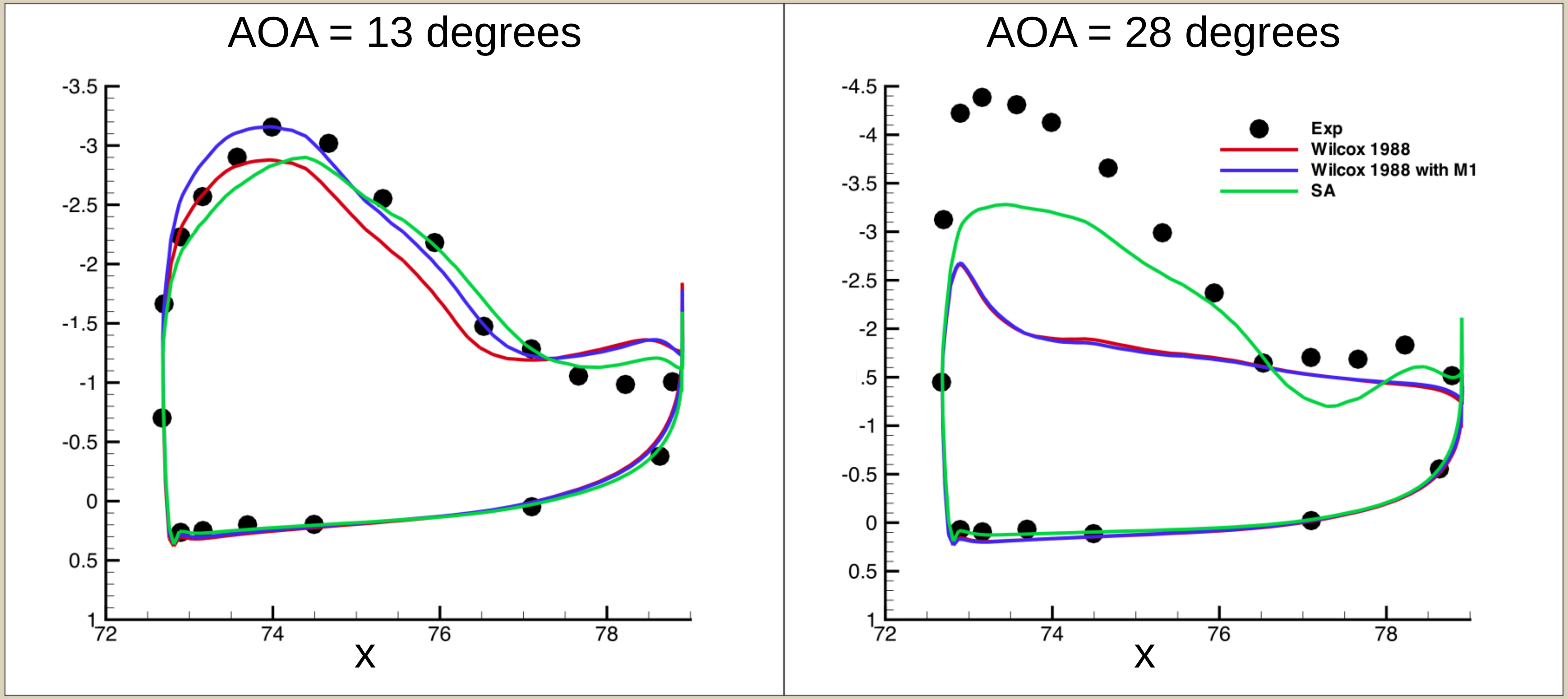

AOA = 13 degrees

AOA = 28 degrees

M1 comparable to SA at AOA=13 degrees.
SA best at AOA=28 degrees.

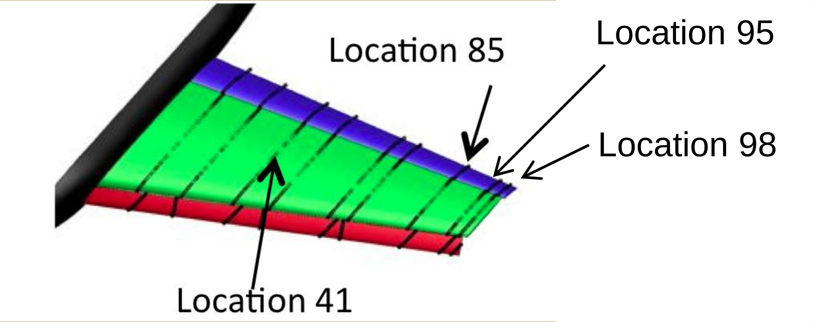
Flap 95

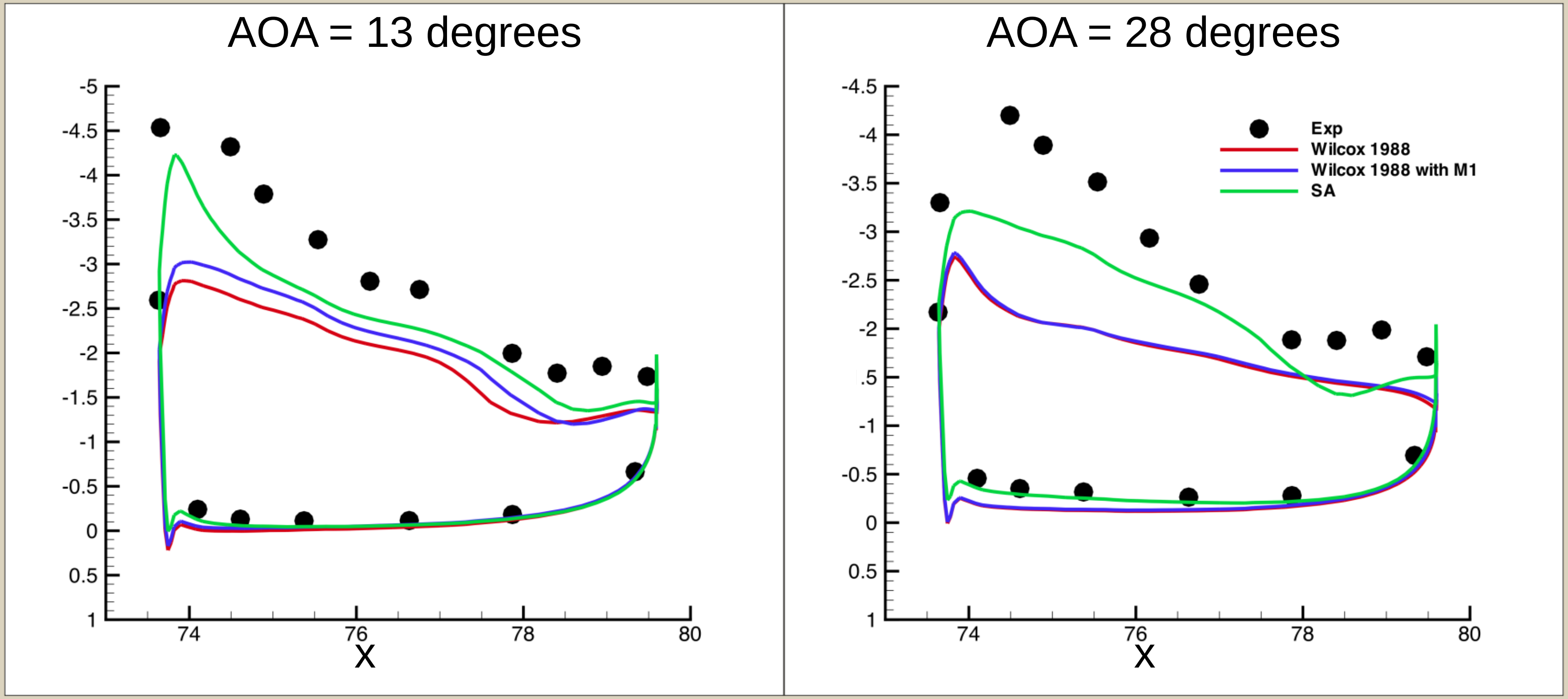




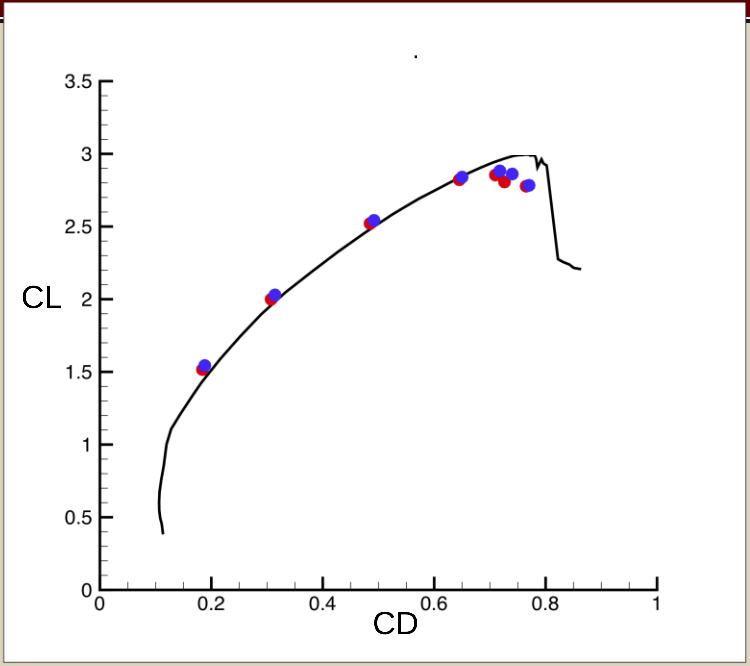
SA and M1 perform marginally better than Wilcox 1988 at AOA=13.

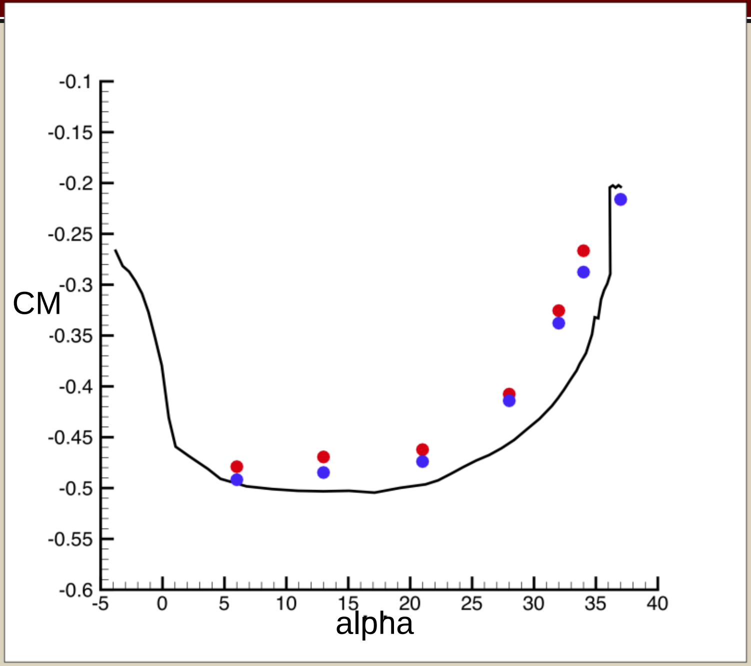
Flap 98





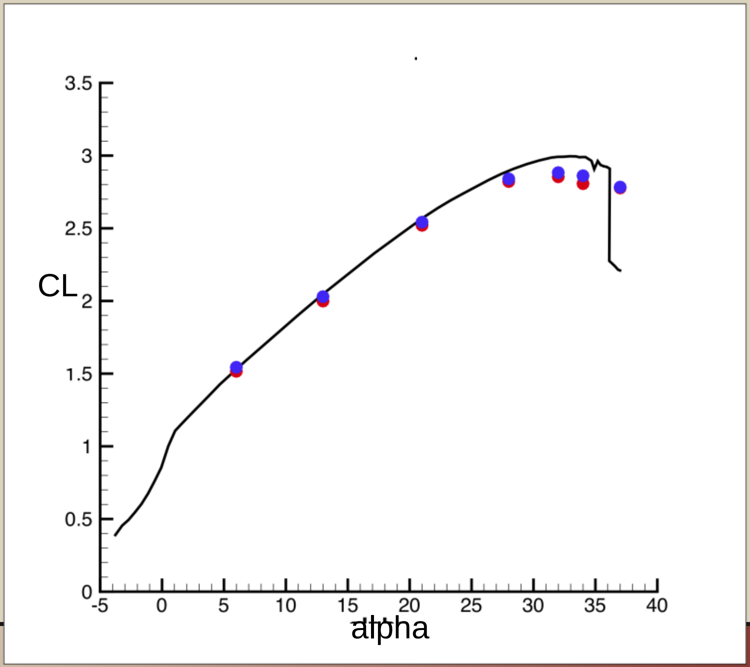
SA performs best.



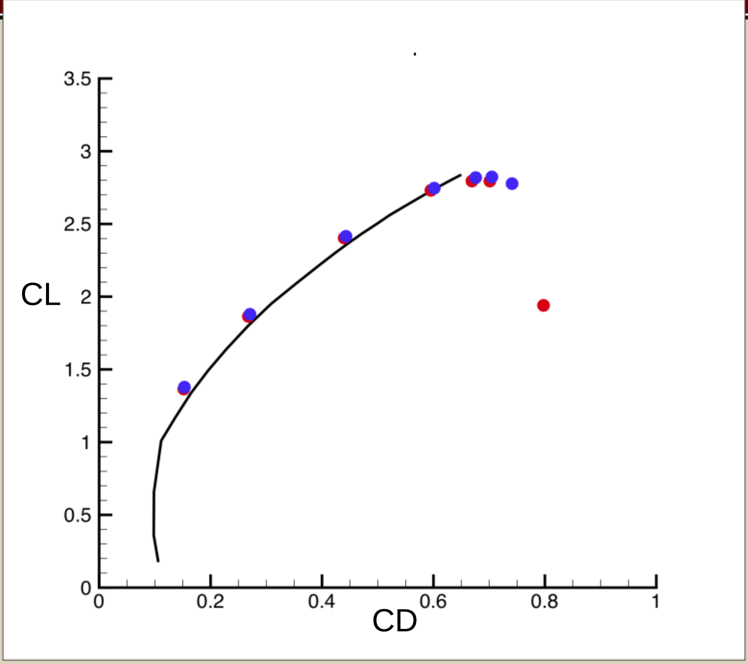


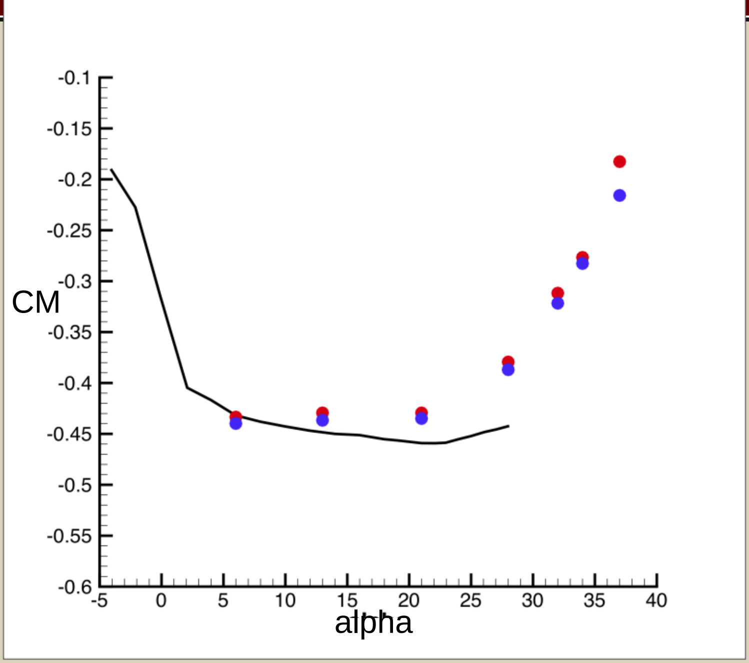
Configuration 1

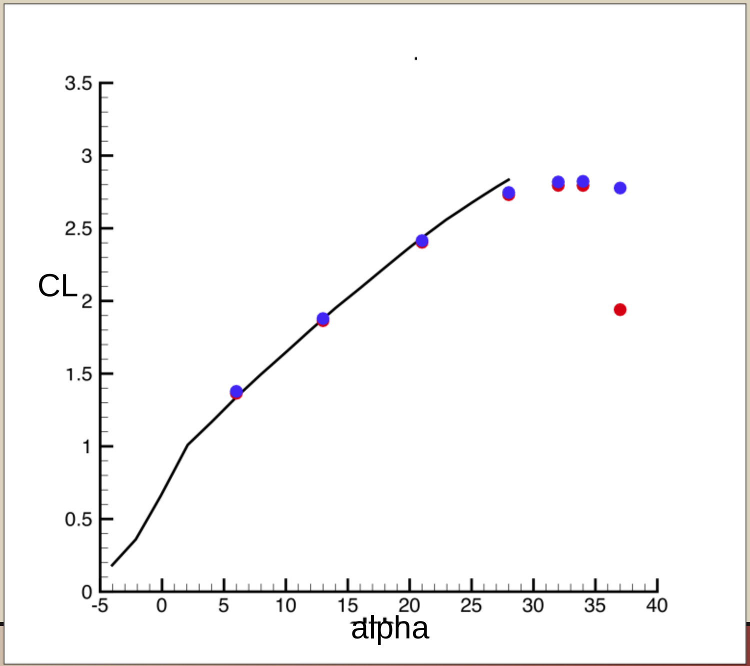
- **EXP**
- ● **Wilcox 1988**
- ● **Wilcox 1988 with M1**



Configuration 2







— EXP
● Wilcox 1988
● Wilcox 1988 with M1

Conclusions

- k-ω model variants tested on wing-body
- Wilcox 2006 found to be unsuitable for this case
  - Developed for jet flows
- M2 model needs further investigation into appropriate implementation
  - Implicit implementation rather than explicit
- M1 is more robust than Wilcox 1988
  - Required no limiter
  - Performed slightly better
- Future Work
  - More careful implementation of M2 model

- Questions?