Improved Turbulence and Transition Modeling Methods for Industrial CFD Simulations

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Outline

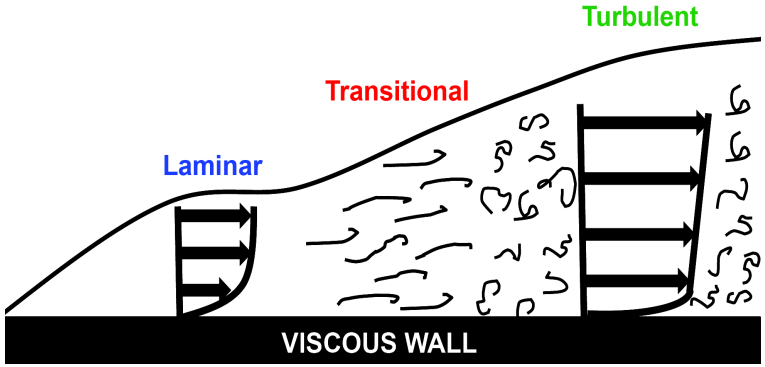
- Introduction
- Motivation and Objectives
- Skin friction drag prediction
  - Streamwise transition
  - Crossflow transition
  - Preliminary Rotor simulations in hover
- Stall prediction
  - Adverse Pressure Gradient sensitivity
  - 2-D static & dynamic stall
- Conclusions

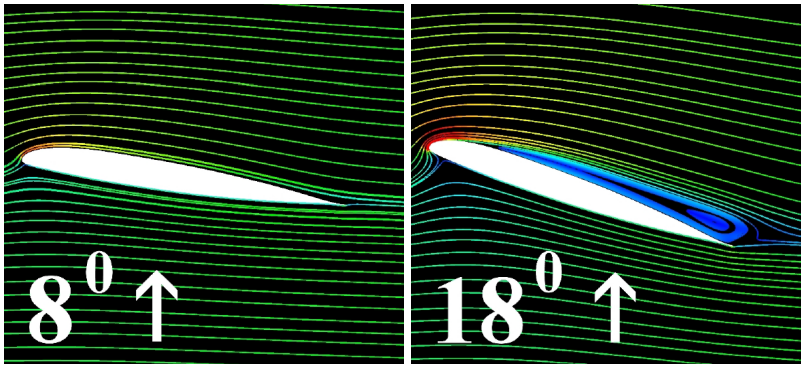
Introduction – Critical Flow Phenomena

- Laminar-Turbulent boundary layer transition
- Shallow and massive flow separation (dynamic stall)
- Blade-vortex interaction, Shock-boundary layer interaction

- Corner flows, Rotor-hub/Landing-gear flows
- Chemistry, heat transfer, vibrations, noise, fatigue

Introduction – Computational Cost





P. Spalart's projection of computational cost to perform DNS/LES on a Boeing wing

DNS – 10^{20} pts, year 2080

LES – 10^{11} pts, year 2045

Spectrum of Approaches to Turbulence

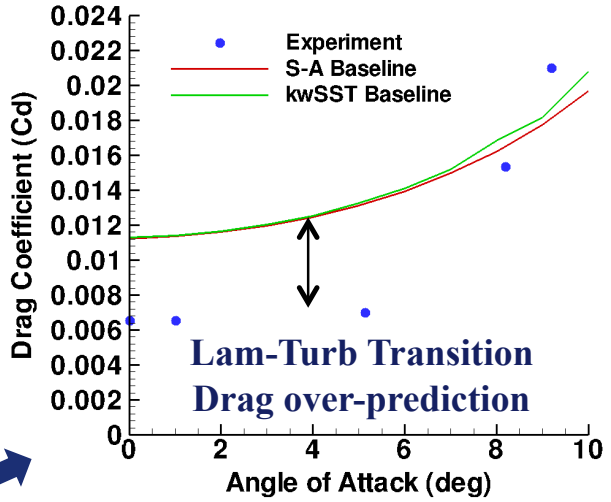
Name	DNS	LES	DES	RANS
Empiricism	No	Low	Medium	High
Unsteady	Yes	Yes	Yes	No (can be)
# of points (Boeing wing)	10^{20}	10^{11}	10^{7} to 10^{8}	10^{7}
In Service (Boeing)	2080*	2045*	2010 (sub-regions)	1995
Vibration, Noise	Yes	Yes	Yes	No (buffet maybe)

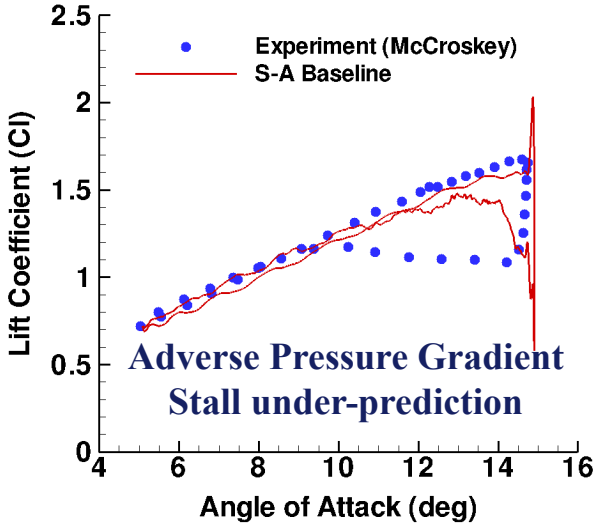
*Assuming Moore's Law holds!

Spalart (2012)

Motivation & Objectives

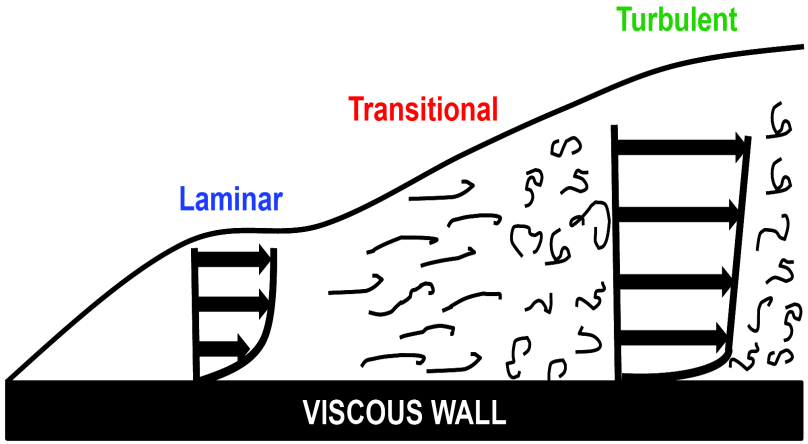
- **Motivation**
  - Improve CFD prediction of critical flow phenomena at reasonable cost
- **Technical Barriers**
  - LES and Hybrid methods expensive for boundary layers at flight Reynolds numbers
  - RANS turbulence/transition models unsatisfactory for certain difficult flow phenomena
- **Objective – Enhance RANS models to**
  - Improve skin drag prediction
  - Improve separation and stall prediction

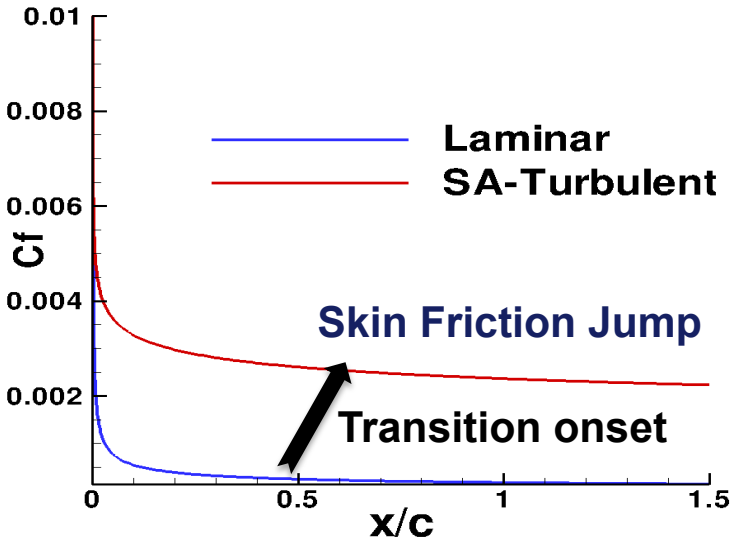




Transition Onset Physics

- **Factors affecting transition**
  - Freestream turbulence
  - Reynolds number
  - Pressure gradients
  - Sweep & Curvature
  - Surface roughness
  - Compressibility, Vibrations
- **Modes of transition (2-D & 3-D)**
  - Natural & Bypass transition (2-D)
  - Separation-inducted transition (2-D)
  - Crossflow transition (3-D)
  - Gortler instabilities (3-D)
  - Attachment-line contamination (3-D)

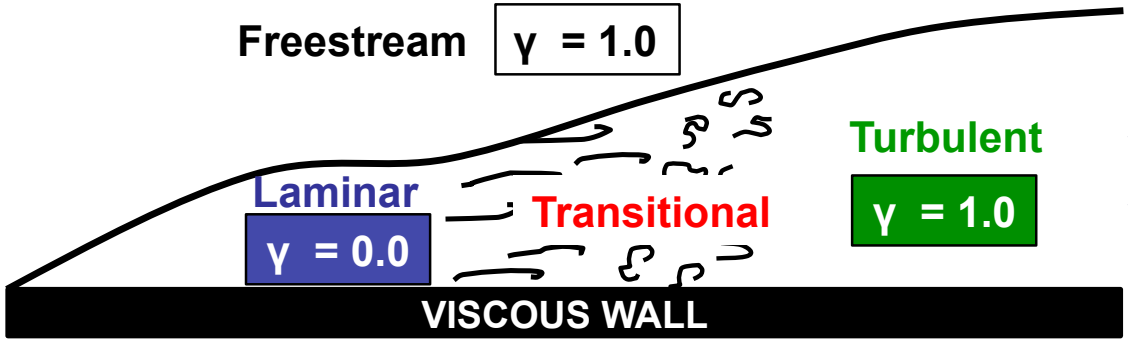




Transition Prediction Methods

- e^N models
  - Smith & Gamberoni (1956), van Ingen (1956)
  - XFOIL – Drela & Giles (1987), MISES – Youngren & Drela (1991)
- Empirical Correlations
  - Michel (1951), Abu-Ghannam & Shaw (1980), Mayle (1990)
  - Owen (1952), Arnal (1984), Kohama (1993)
- Intermittency-transport models
  - Cho & Chung (1992), Steelant & Dick (1996), Suzen & Huang (2000)
  - γ-Re_θ Model for k-ω SST turbulence model – Langtry & Menter (2004)
    - Natural, Bypass, and Separation-induced transition
    - Fully local formulation – compatible with structured/unstructured solvers
    - Account for history effects through transport equations
    - Extended for Spalart-Allmaras model – Medida & Baeder (2011)
    - N-factor transport model (replacing Re_θ) – Coder (2013)

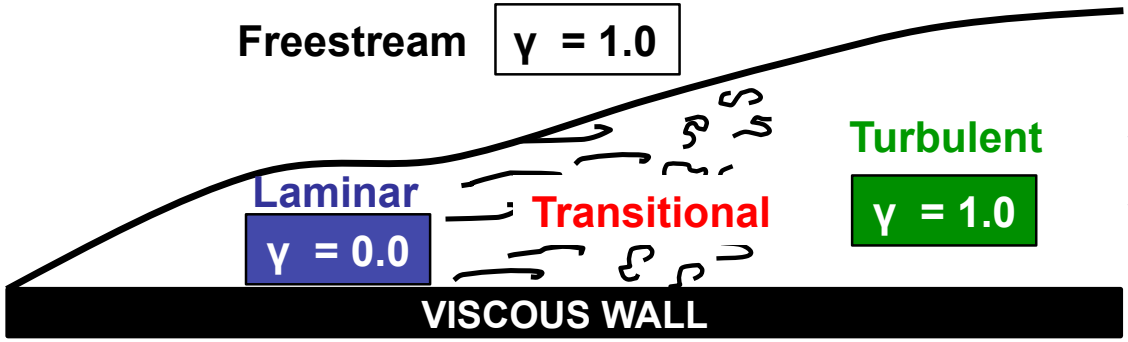
γ-Re_θ Transition Model for k-ω Turbulence Model (Langtry, 2004)



γ = 0 – Turbulence Production OFF

γ = 1 – Turbulence Production ON

γ-Re_θ Transition Model for k-ω Turbulence Model (Langtry, 2004)



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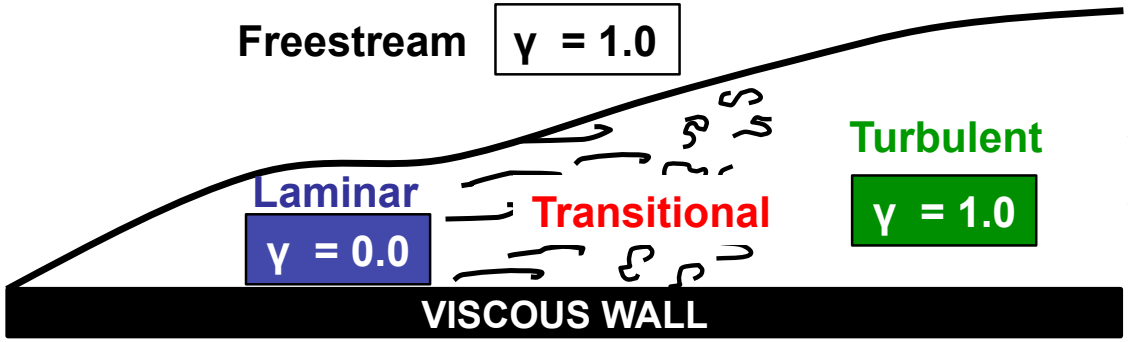
Experimental Correlation for Transition Momentum Thickness Reynolds Number

$$Re_{\theta t} = fn(Tu_\infty, \lambda)$$

Freestream turbulence intensity, Local pressure gradient

Need Local Formulation to Detect Transition Onset

γ-Re_θ Transition Model for k-ω Turbulence Model (Langtry, 2004)



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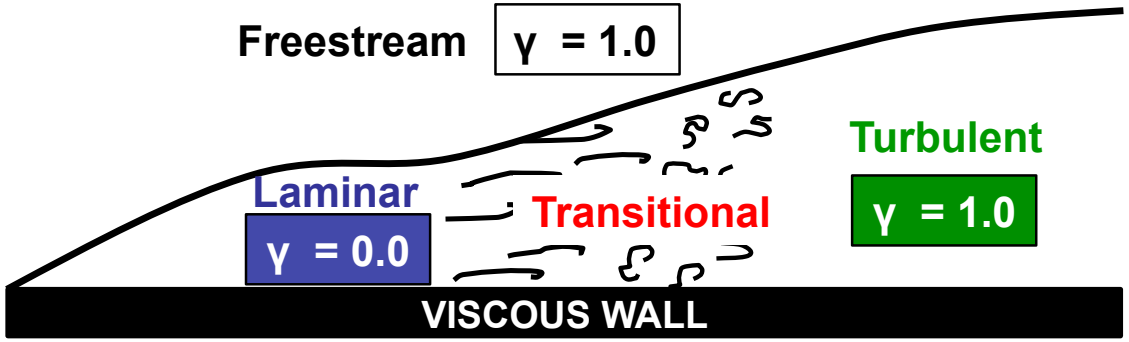
$$\frac{D\left(\overline{\mathrm{Re}_{\theta t}}\right)}{Dt} = P_{\theta t} - D_{\theta t} + M_{\theta t}$$

Experimental Correlations

- Two transport equations (P – Production, D – Destruction, M – diffusion)
  - Transition Momentum Thickness Reynolds Number – $Re_{\theta t} = fn(Tu_\infty, \lambda)$

γ-Re_θ Transition Model for k-ω Turbulence Model (Langtry, 2004)



Key Innovation

Fully local onset criterion

$$\frac{D\left(\overline{\mathrm{Re}_{\theta t}}\right)}{Dt} = P_{\theta t} - D_{\theta t} + M_{\theta t}$$

$$\beta = \frac{\max\left(\mathrm{Re}_v\right)}{2.193.\mathrm{Re}_\theta} > 1, \quad \mathrm{Re}_v = \frac{\rho y^2 S}{\mu}$$

Experimental Correlations

Vorticity Rey. No / Transition Momentum Thickness Rey. No

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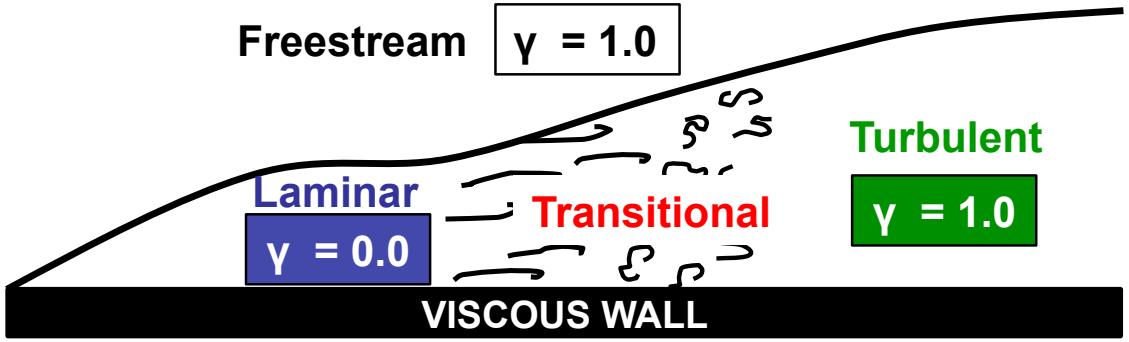

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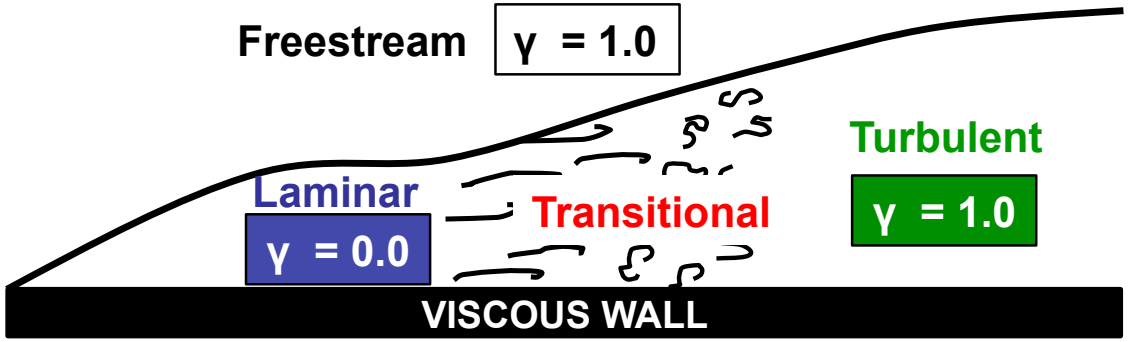
$$\frac{D\gamma}{Dt} = P_\gamma - D_\gamma + M_\gamma$$

Experimental Correlations → ***Vorticity Rey. No / Transition Momentum Thickness Rey. No*** → ***Onset criterion***

- **Two transport equations (P – Production, D – Destruction, M – diffusion)**
  - **Transition Momentum Thickness Reynolds Number – $Re_{\theta t} = fn(Tu_\infty, \lambda)$**
  - **Intermittency – 0 (laminar) ≤ γ ≤ 1 (turbulent), $P_\gamma = Fn(\beta)$**

γ-Re_θ Transition Model for k-ω Turbulence Model (Langtry, 2004)



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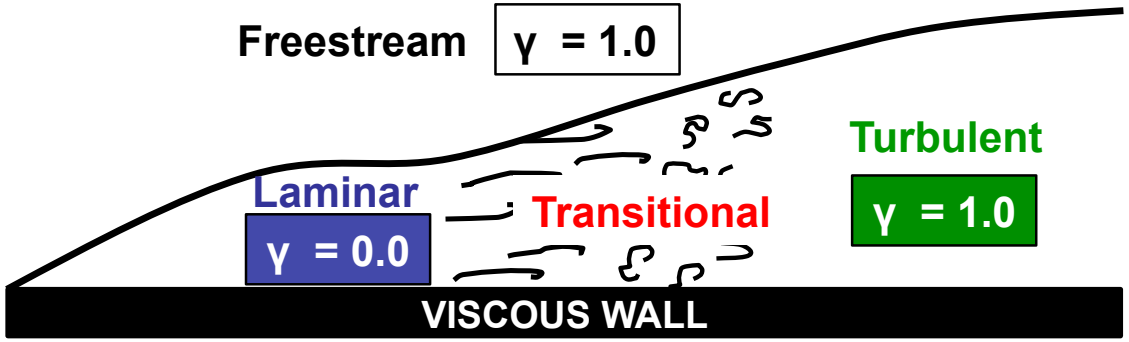

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$$\frac{D\gamma}{Dt} = P_\gamma - D_\gamma + M_\gamma$$

Experimental Correlations → ***Vorticity Rey. No / Transition Momentum Thickness Rey. No*** → ***Onset criterion***

- **Scaled production and destruction of Turbulent Kinetic Energy**
  - $P_{TKE_new} = \gamma.P_{TKE_original}$, $D_{TKE_new} = \min(\max(\gamma,0.1),1.0).D_{TKE_original}$

γ-Re_θ Model for Spalart-Allmaras Turbulence Model (Medida, 2011)

Destruction need not be scaled

Spalart-Allmaras Model $\Rightarrow$ $\frac{D\mu_t}{Dt} = P_\mu - D_\mu + M_\mu$

Modified S-A Model $\Rightarrow$ $\frac{D\mu_t}{Dt} = \gamma P_\mu - D_\mu + M_\mu$

γ-Re_θ Model for Spalart-Allmaras Turbulence Model (Medida, 2011)

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$$\text{Spalart-Allmaras Model} \Rightarrow \frac{D\mu_t}{Dt} = P_\mu - D_\mu + M_\mu$$

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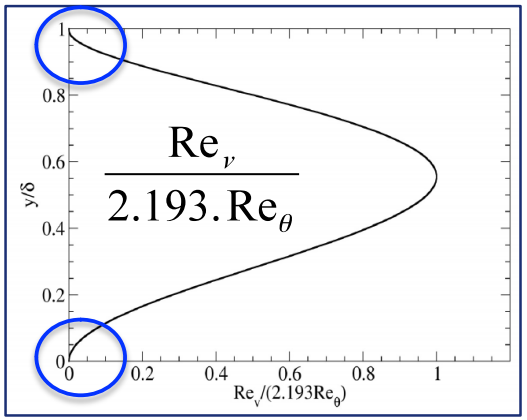
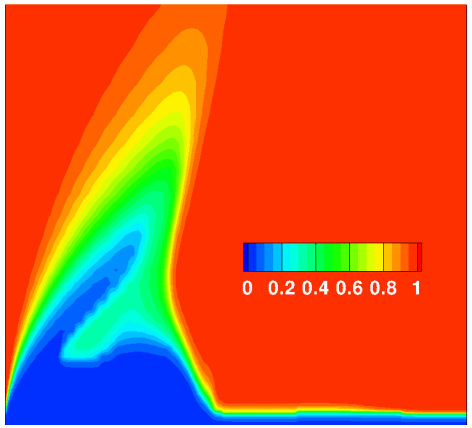
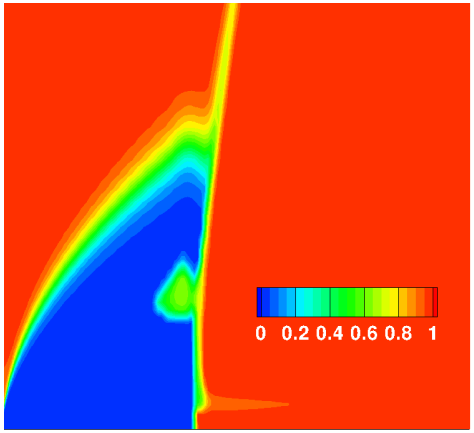
Transition onset criterion not satisfied at edges of turbulent BL







Flat Plate Intermittency Contours

Blue – OFF

Red – ON

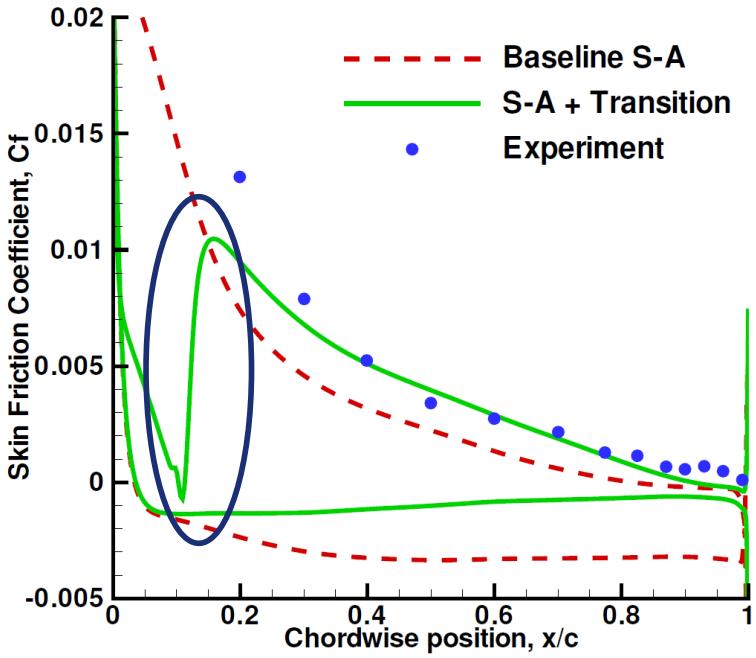
$$Re_v = \frac{\rho y^2 S}{\mu}$$

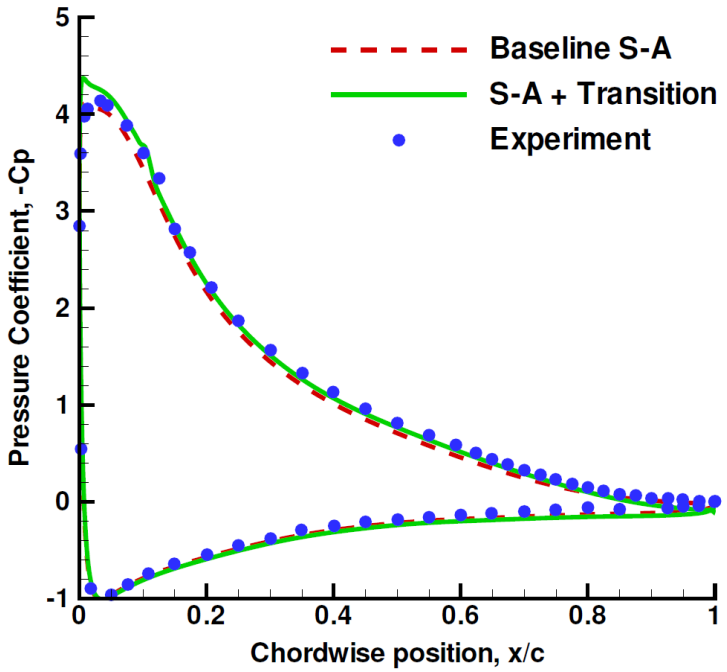
Original **Improved**

Modified Intermittency production and destruction terms

Aerospatiale-A Airfoil – Transition Onset at 12% Chord

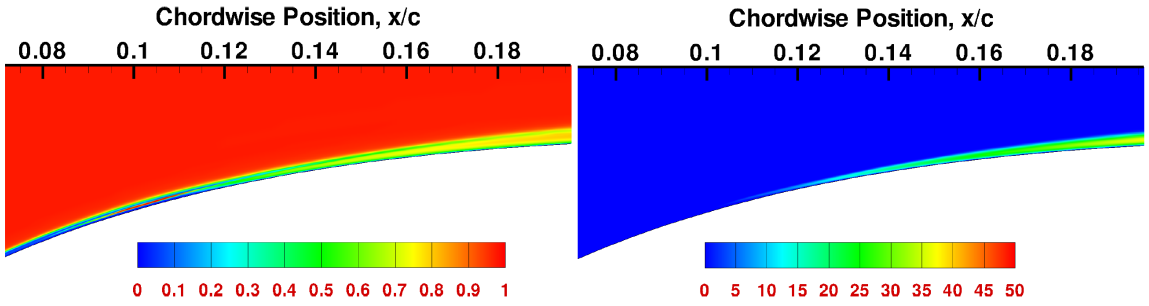
M = 0.15, Re = 2x10^6 , AoA = 13.1°, Tu ~ 0.05%





- Skin friction jump at 12% of chord on upper surface indicates transition onset
- Lower surface fully laminar

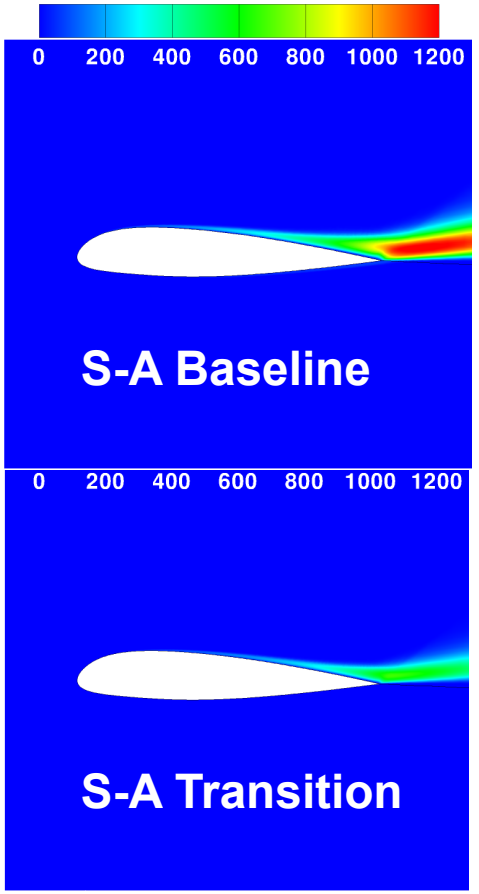
Aerospatiale-A Airfoil – Transition Onset at 12% Chord



Intermittency Eddy Viscosity

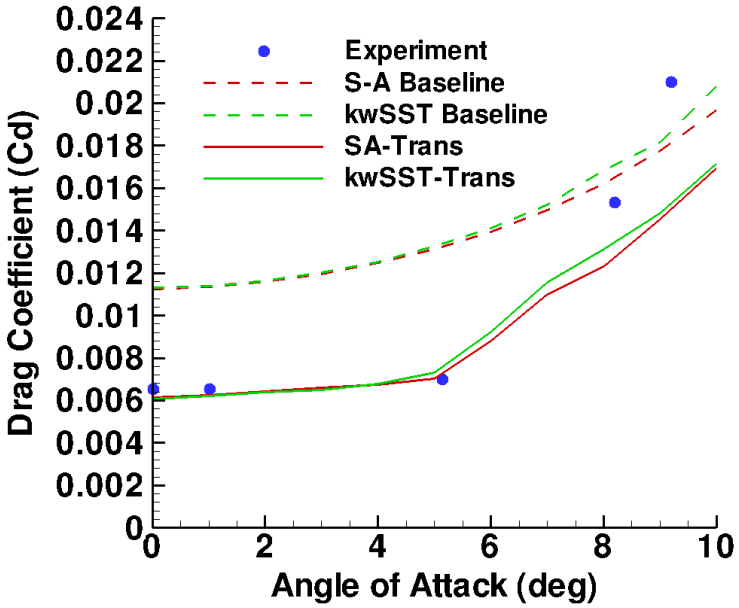
Blue – Turbulence production is OFF

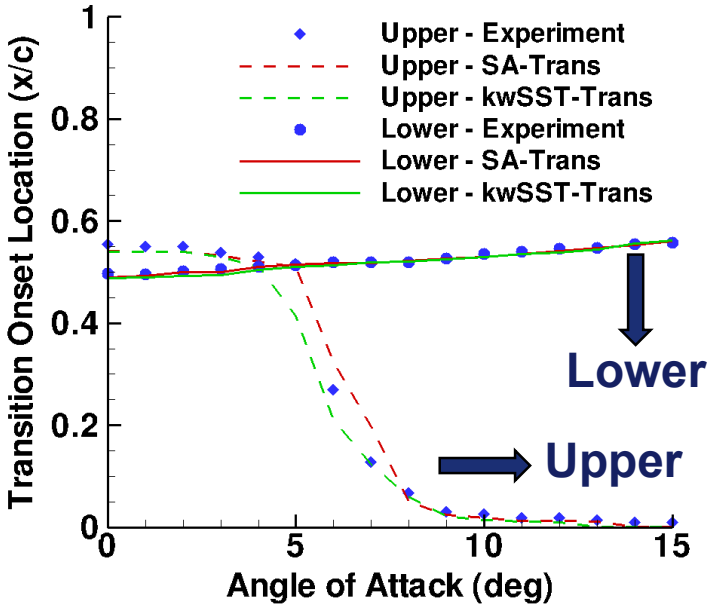
Red – Turbulence production is ON



Eddy Viscosity

S809 Laminar-Flow Airfoil, Re = 2x10^6 (D. M. Somers, 1997)

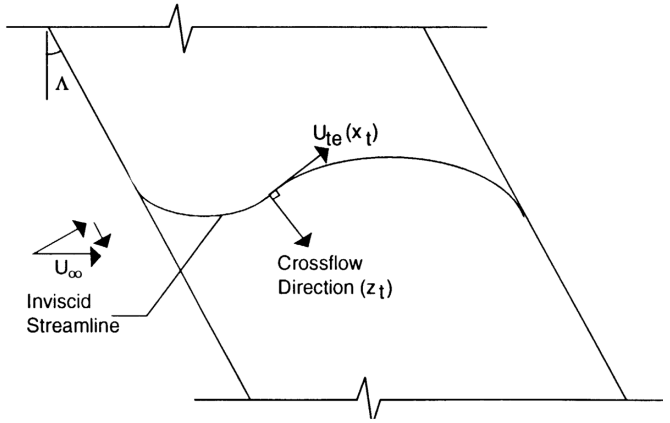


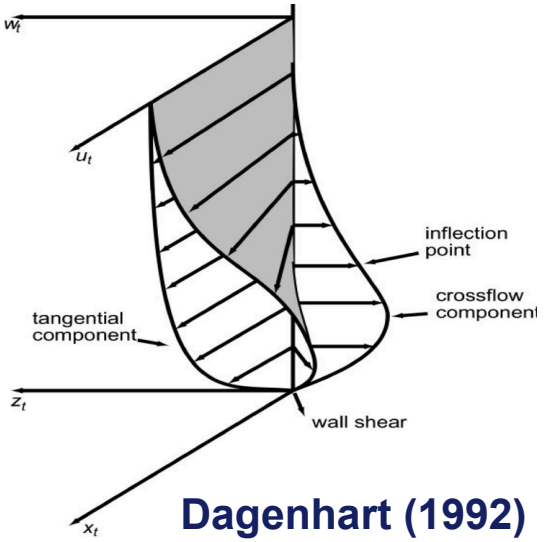


- **Significantly improved drag prediction at lower AoA**
- **Transition onset locations well predicted at all AoA**
  - **X_{T_UPPER} moves upstream, X_{T_LOWER} moves downstream with increasing AoA**
  - **This is 2-D streamwise transition. What happens in 3-D boundary layers?**

Crossflow Transition Modeling

- Inflectional instability of crossflow velocity profile triggers transition in 3-D BLs
- Transition onset location moves upstream
  - Adverse pressure gradient in 2-D
  - Favorable pressure gradient in 3-D





Dagenhart (1992)

Crossflow Transition Modeling

- Inflectional instability of crossflow velocity profile triggers transition in 3-D BLs
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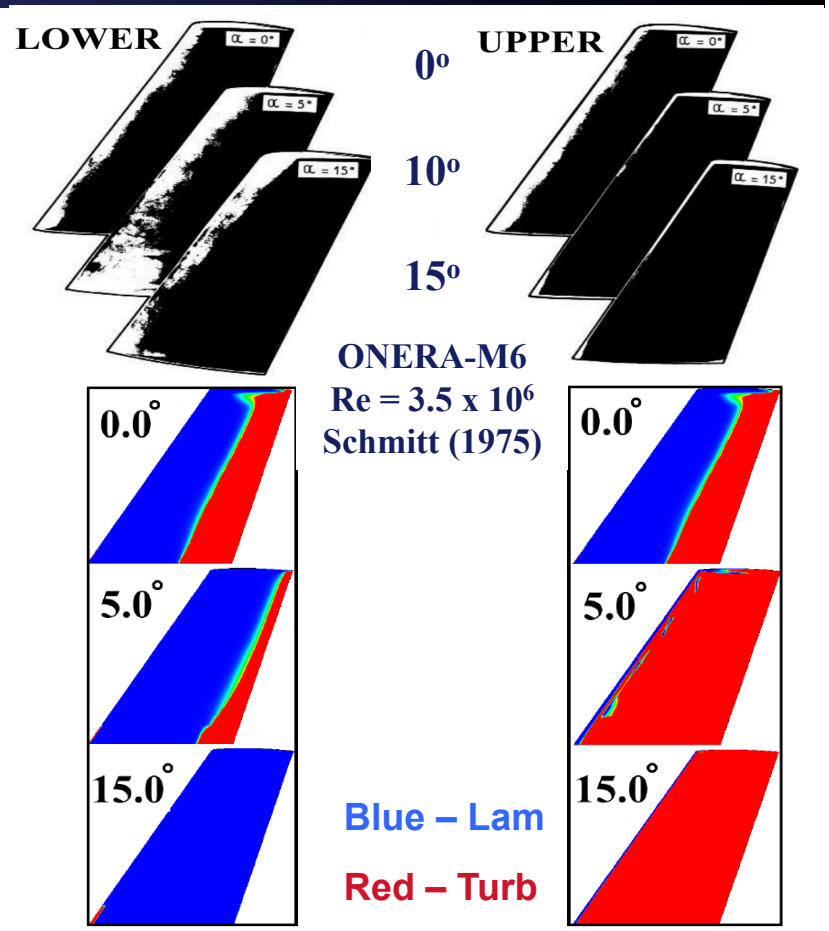
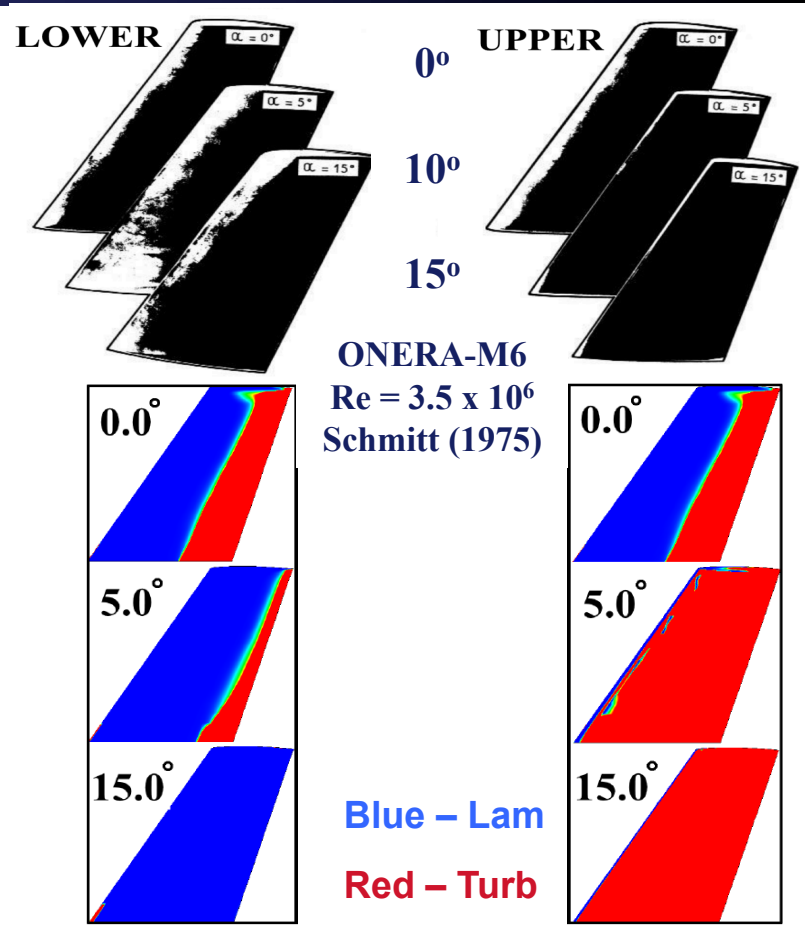
- Drag under-prediction if crossflow ignored



Baseline γ-Re_θ–SA model predictions

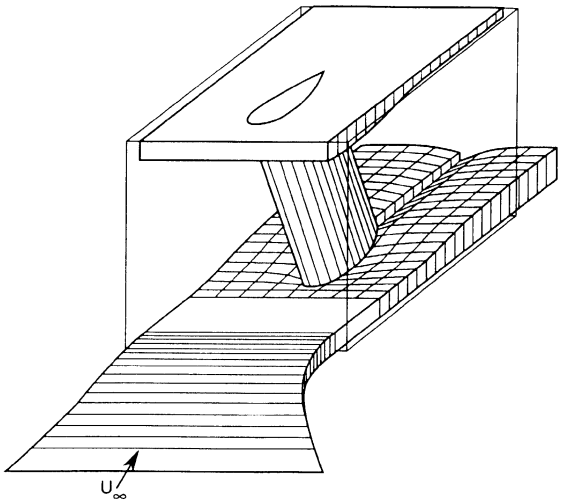
Crossflow Transition Modeling

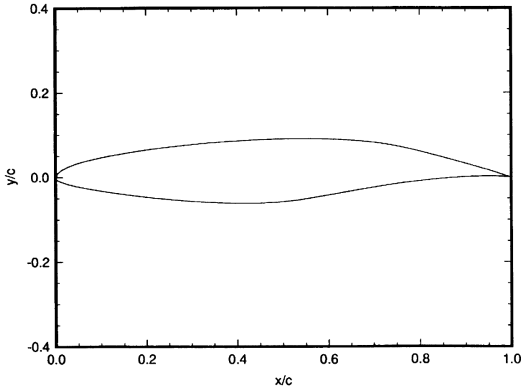
- Inflectional instability of crossflow velocity profile triggers transition in 3-D BLs
- Transition onset location moves upstream
  - Adverse pressure gradient in 2-D
  - Favorable pressure gradient in 3-D
- Drag under-prediction if crossflow ignored
- Crossflow Prediction Methods
  - Owen (1952), Arnal (1984), Kohama (1993)
  - New crossflow criterion suitable for γ-Re_θ transition model?

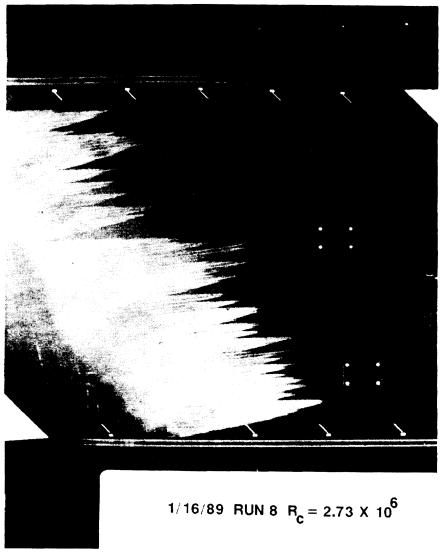


Baseline γ-Re_θ–SA model predictions

New Crossflow Transition Onset Criterion (Medida, 2013)

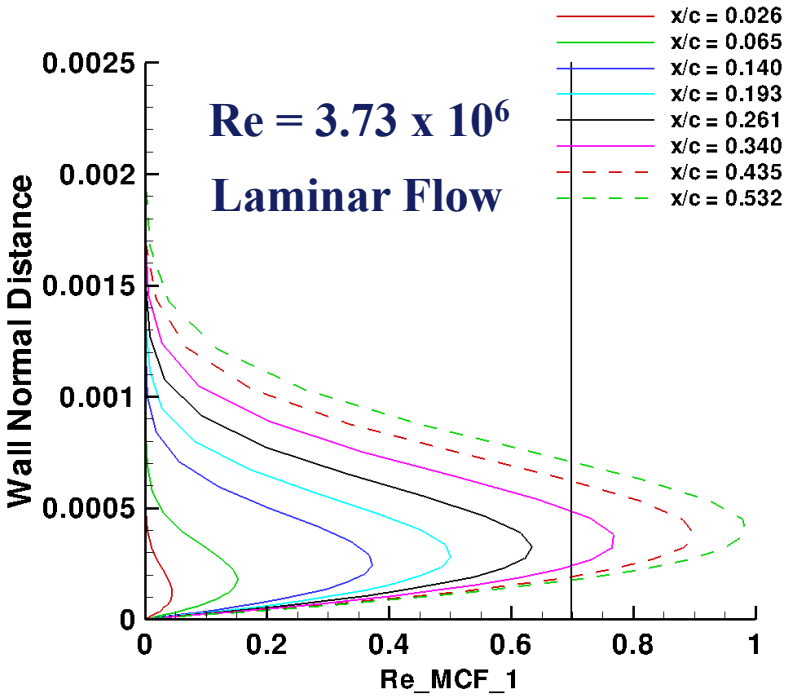






- Infinite swept-wing experiments (Dagenhart, 1992)
  - NLF(2)-0415 airfoil section, Sweep angle = 45°
  - Pure crossflow instability on upper surface at -4° AoA
  - Variation of transition onset location with freestream Reynolds number
  - Simulate Laminar flow and examine profiles of non-dimensional parameters
  - Inviscid Streamline Radius of Curvature (R), Crossflow velocity (U_{CF})

New Crossflow Transition Onset Criterion (Medida, 2013)



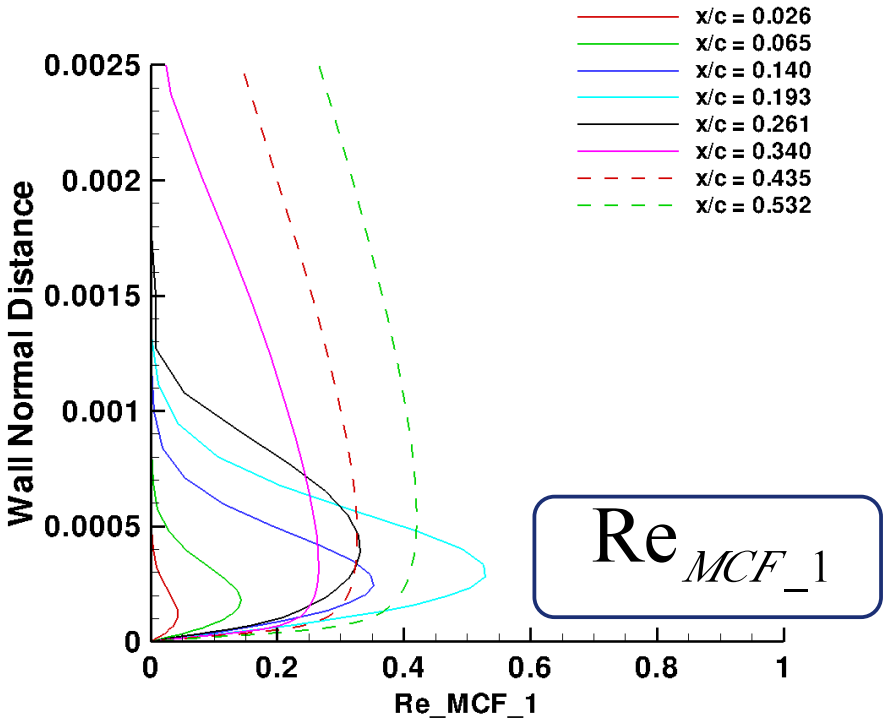
Reynolds Number	CFD Onset Location	Expt Onset Location
1.92×10^6	0.68	0.70 - 0.85
2.37×10^6	0.52	0.48 – 0.68
2.73×10^6	0.43	0.40 – 0.65
3.27×10^6	0.35	0.20 – 0.45
3.73×10^6	0.32	0.20 – 0.40

$$U_{CF_1} = \left| u.r_1 + v.r_2 + w.r_3 \right|$$

$$\mathrm{Re}_{MCF_1} = \frac{U_{CF_1} |R|}{\upsilon} F_{BL} > 0.7$$

Re_{MCF_1} onset criterion in reasonable agreement with experimental data

New Crossflow Transition Onset Criterion (Medida, 2013)



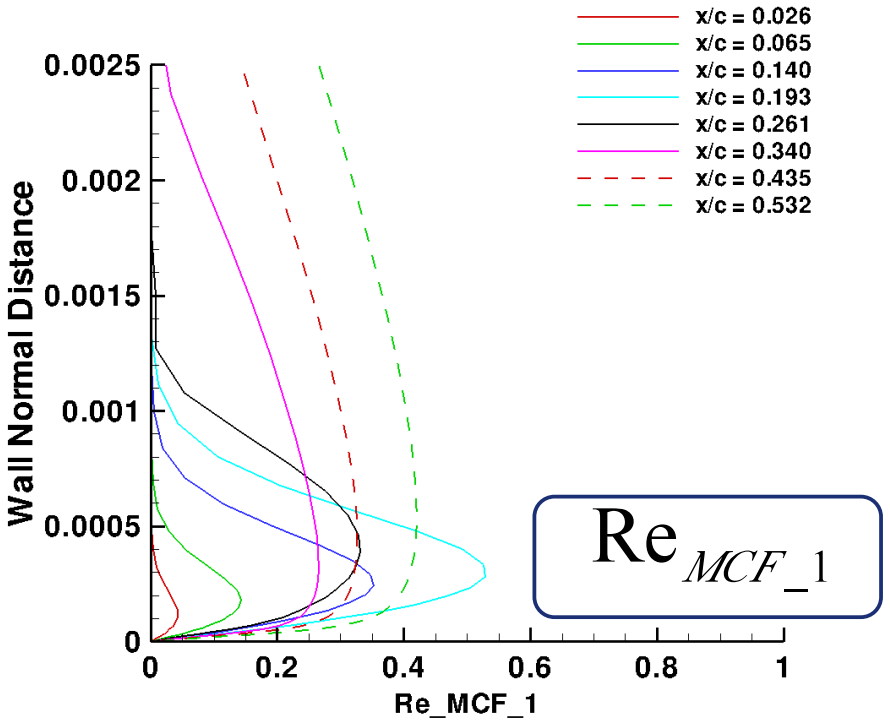
$$Re_{MCF_1}$$

Tripped at 25% chord, Re = 3.73 x 10^6

Peak values drop post-transition onset

Cannot use for unsteady flows!

New Crossflow Transition Onset Criterion (Medida, 2013)



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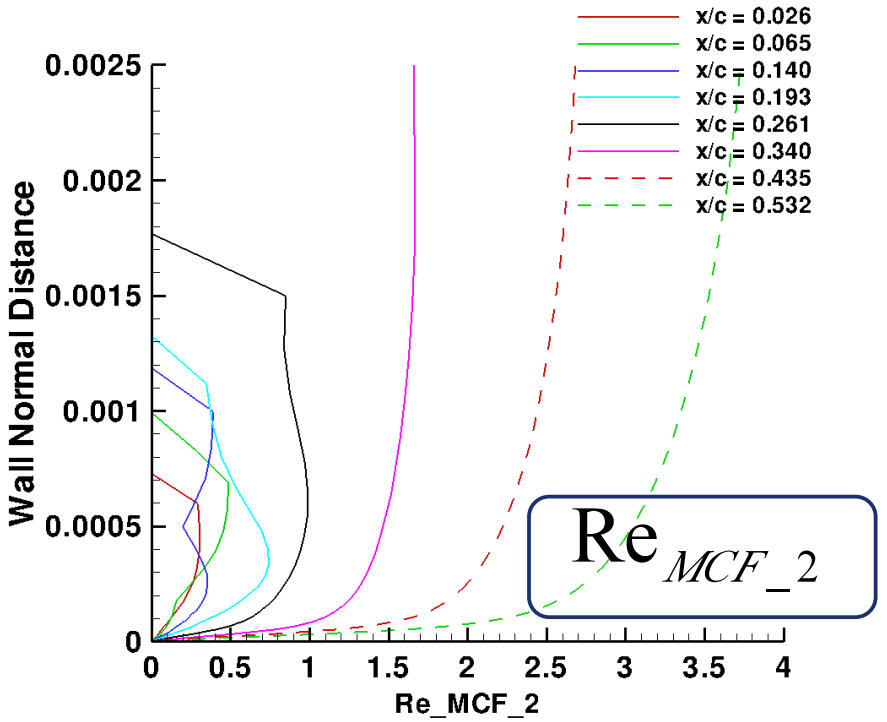


$$Re_{MCF_2}$$

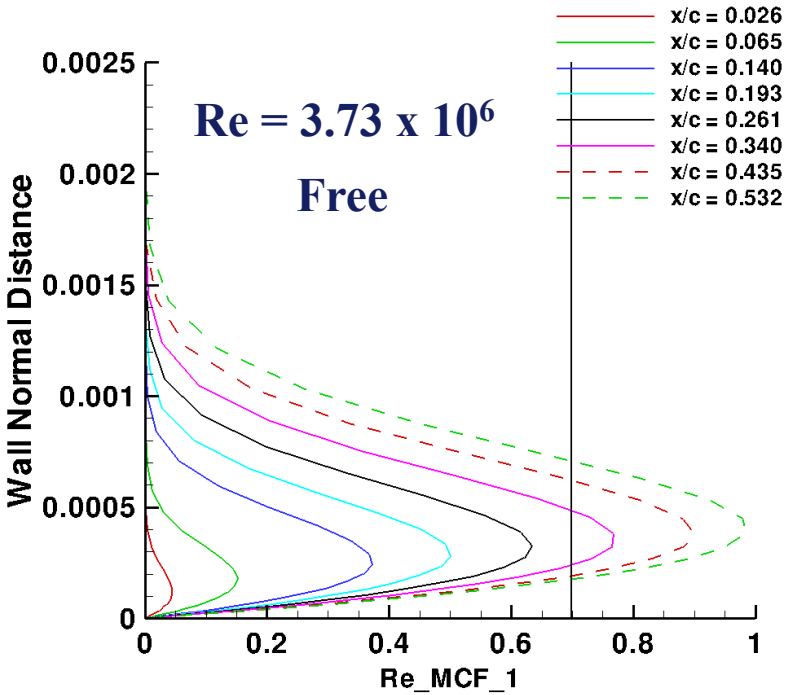
Tripped at 25% chord, Re = 3.73 x 10^6

Peak values drop post-transition onset

Cannot use for unsteady flows!

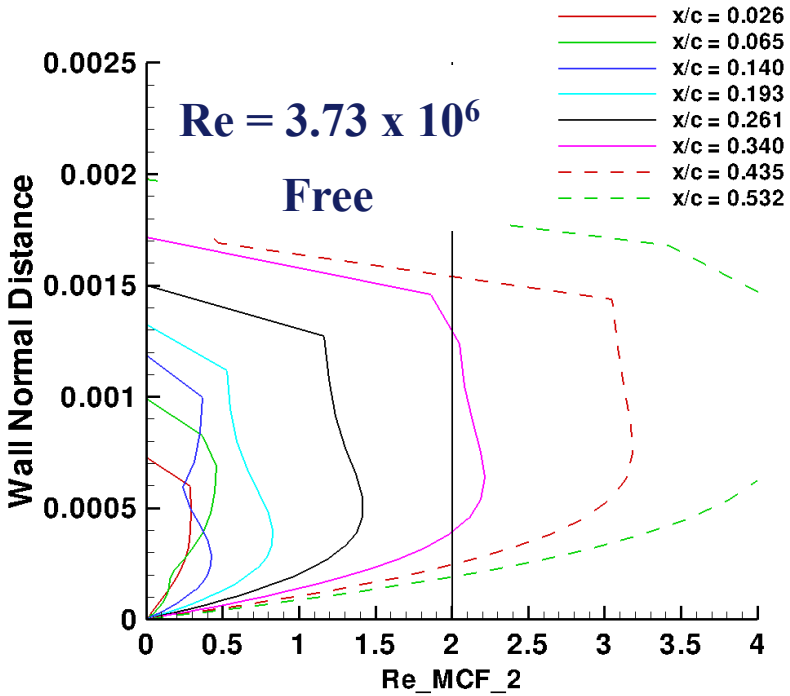
Peak values continue to increase post-transition

New Crossflow Transition Onset Criterion (Medida, 2013)



$$U_{CF_1} = \left| u.r_1 + v.r_2 + w.r_3 \right|$$

$$\mathrm{Re}_{MCF_1} = \frac{U_{CF_1}|R|}{\upsilon} F_{BL}$$

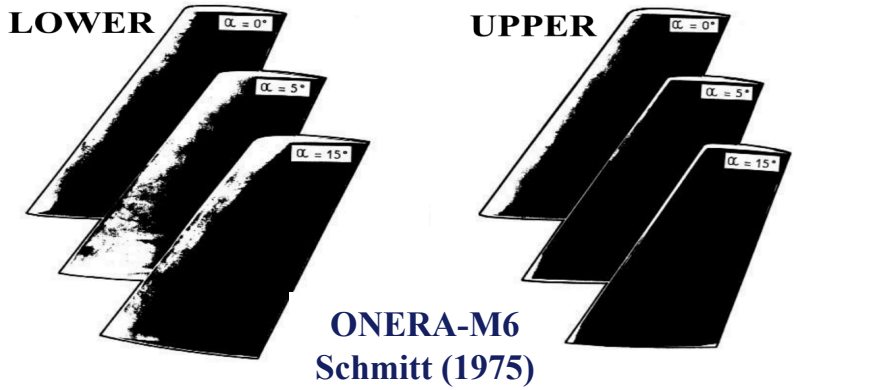


$$U_{CF_2} = \left| u.r_1 \right| + \left| v.r_2 \right| + \left| w.r_3 \right|$$

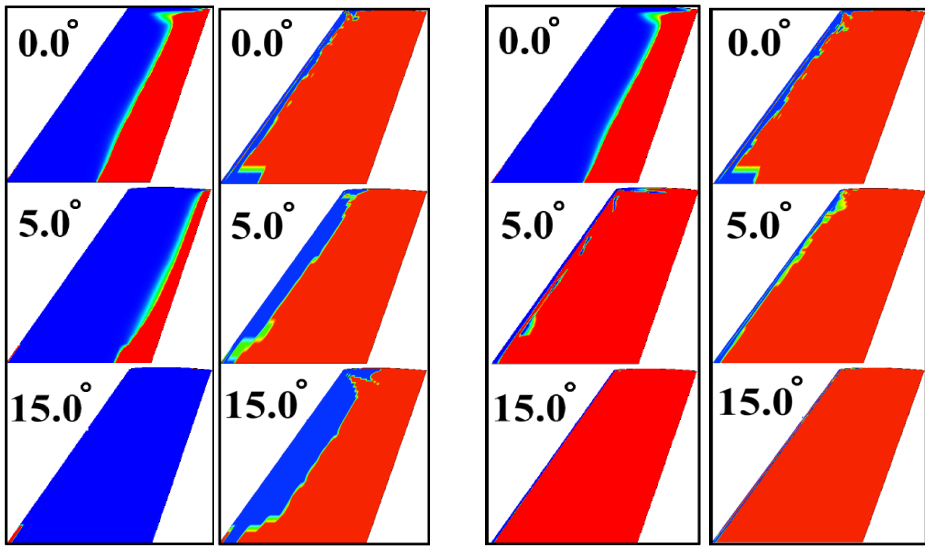
$$\mathrm{Re}_{MCF_2} = \frac{U_{CF_2}|R|}{\upsilon} F_{BL}$$

ONERA M6 Wing with Crossflow Transition Modeling

- Improved γ-Re_θ–SA model predictions on lower surface of ONERA-M6 wing using new crossflow onset criterion
- Apply to fuselage geometries, and moving bodies



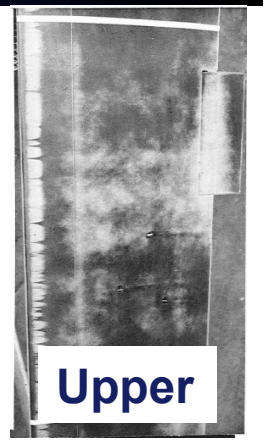
ONERA-M6
Schmitt (1975)



Baseline Improved Baseline Improved

Role of Transition in Rotorcraft Flows

- **Experiments**
  - UH-1B (Tanner, 1966), NACA 0015 model rotor (Velkoff, 1971)
    - Laminar up to 30% main rotor, 50% tail rotor chord
  - BO 105 rotor in hover (Rohardt, 1987)
    - Laminar up to 22% upper surface, 70% lower surface
- **CFD w/ Transition Models**
  - 7AD rotor in forward flight (Beaumier, 1995)
    - Integral BL method, 2% reduction in power
  - UH60-A rotor in forward flight, Robin Fuselage (Zografakis, 2008)
    - Comparison of transition prediction methods
  - BO 105 rotor in hover & 7AD in forward flight (Heister, ’12, ‘13)
    - Correlation-based onset criterion, 2 ~ 5% reduction in power

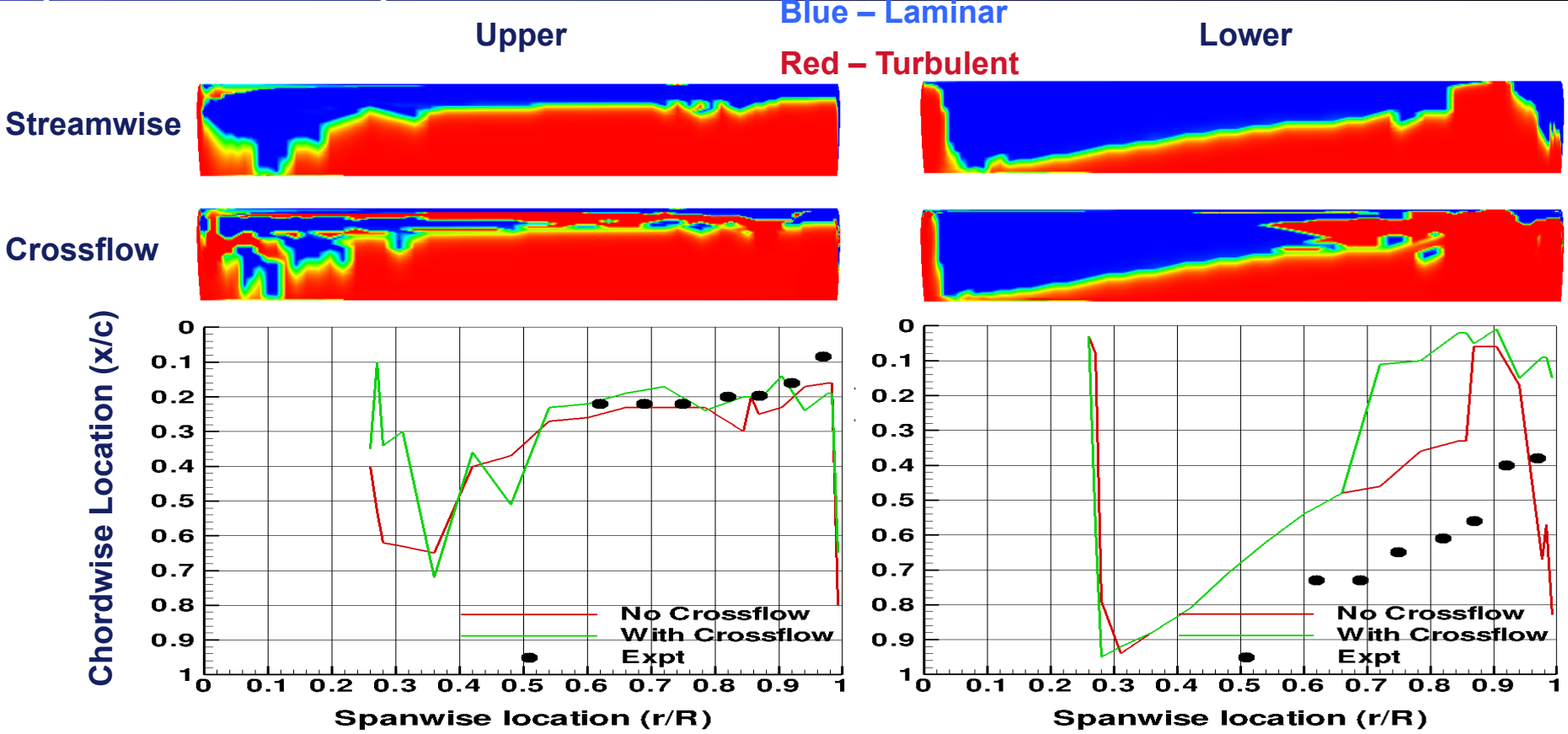


UH-1B Main Rotor
Tanner (1966)

Preliminary BO 105 Rigid Rotor Simulations in Hover (10° collective)

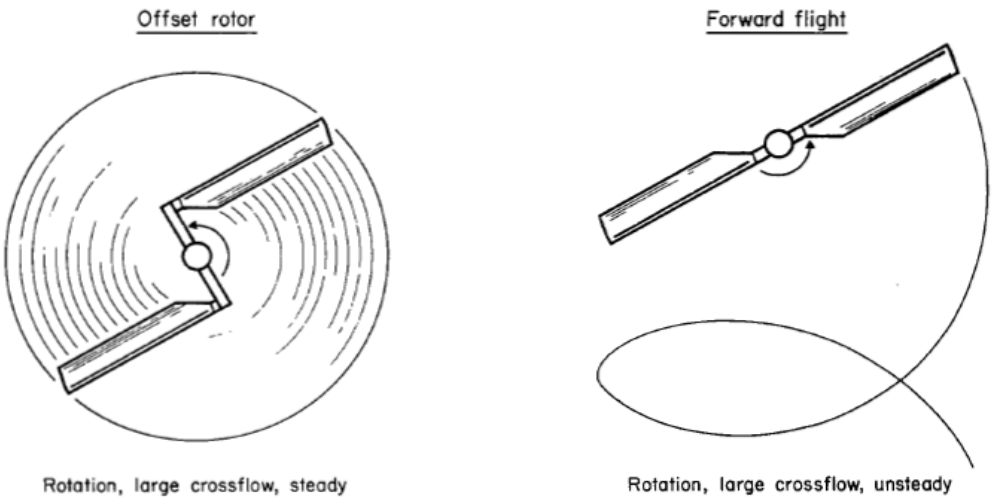
Blue – Laminar

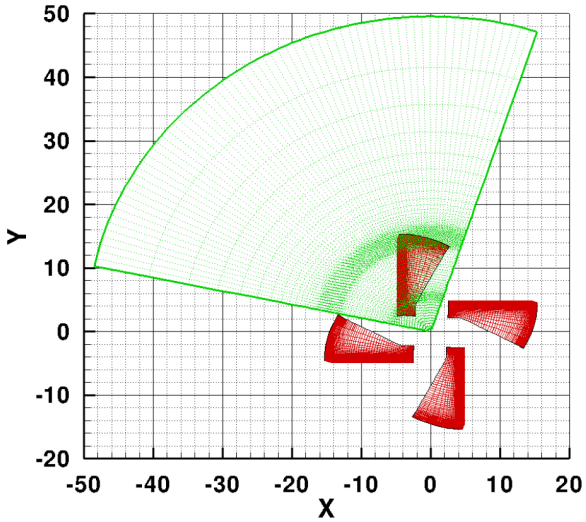
Red – Turbulent



- BO 105 rotor experiments of Rohardt (1987), data digitized from CFD work of Heister (2012)
- 4.5% reduction in total power with streamwise transition, 2.0% reduction with crossflow transition

UH60-A Offset Rotor Simulations





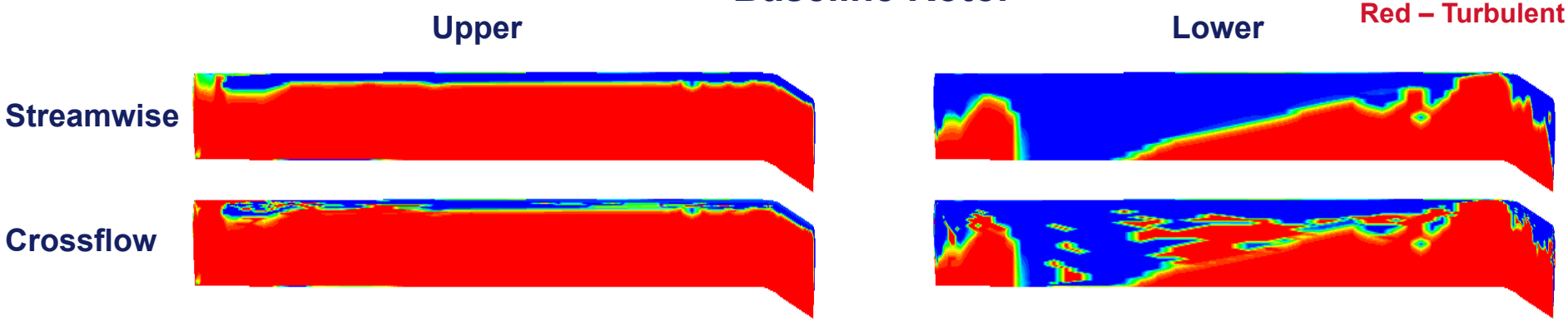
- Concept borrowed from McCroskey's experiments (1971)
  - *Yawed flow in hover to simulate forward flight*
- UH60-A rigid rotor in hover at 10° collective
  - Baseline Vs Offset – qualitative comparison

UH60-A Offset Rotor Simulations

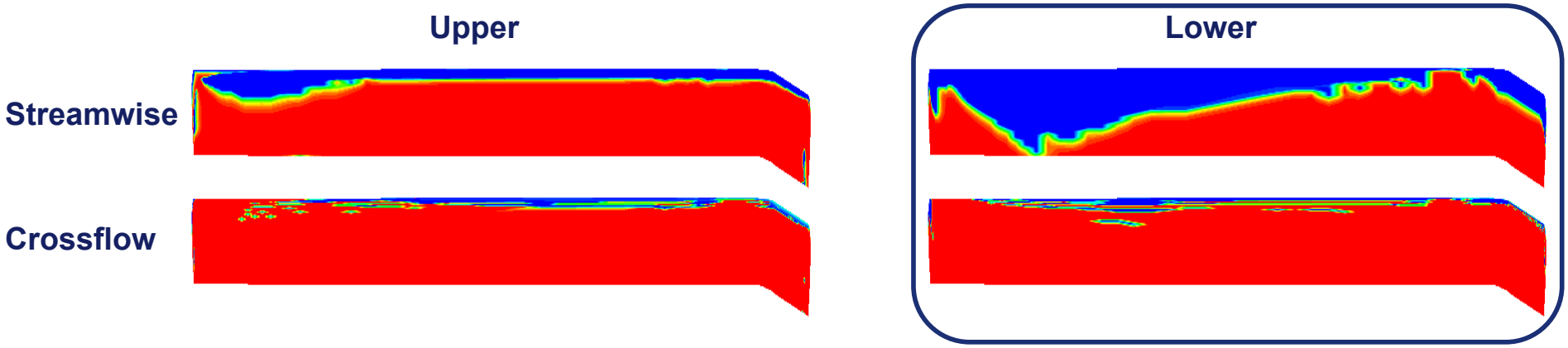
Blue – Laminar

Red – Turbulent

Baseline Rotor



Offset Rotor

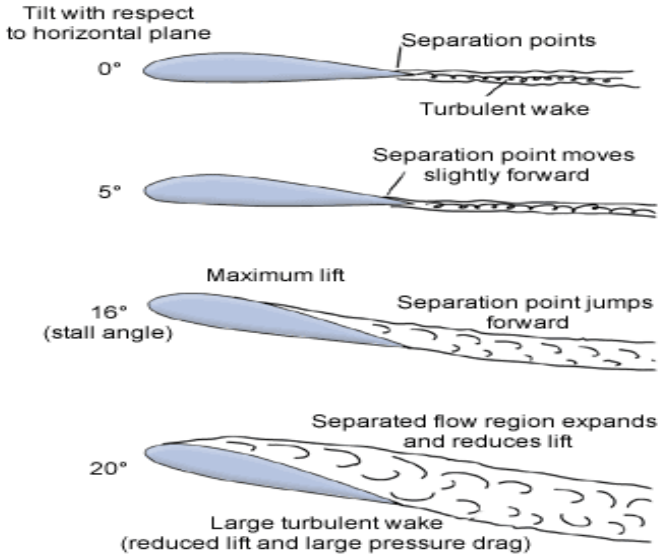


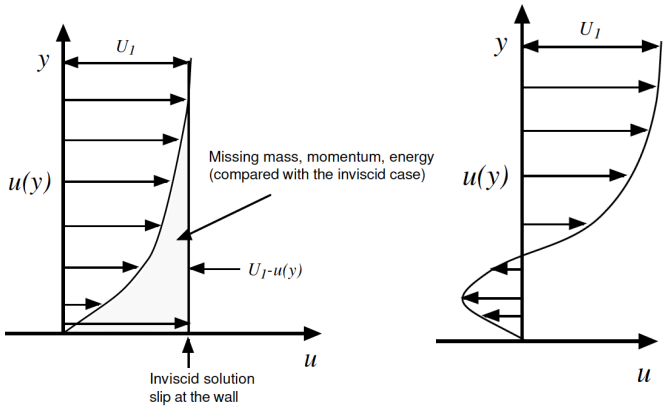
Comments on Transition Modeling Work

- Crossflow Modeling needs further calibration and testing for unsteady flows
- Rotor simulation efforts are in preliminary stage
  - Any rotation effects? Surface roughness?
  - What about upstream blade wake's turbulence transport?
  - Grid sensitivity study

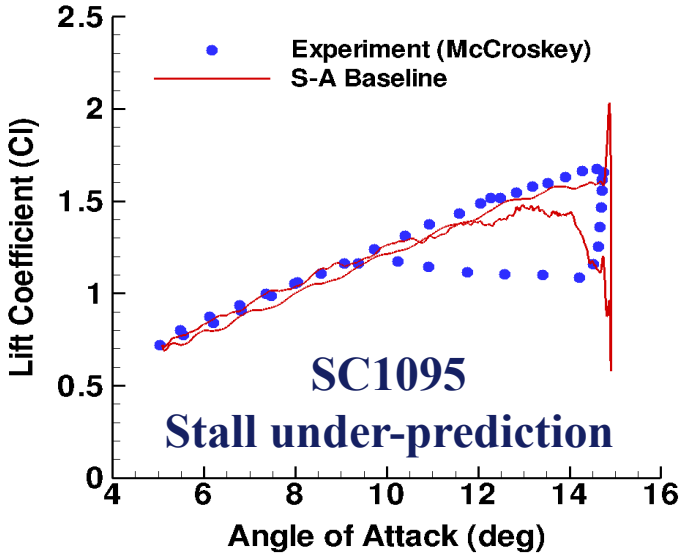
Improved Stall Prediction with RANS Turbulence Models

Stall Prediction with RANS Turbulence Models

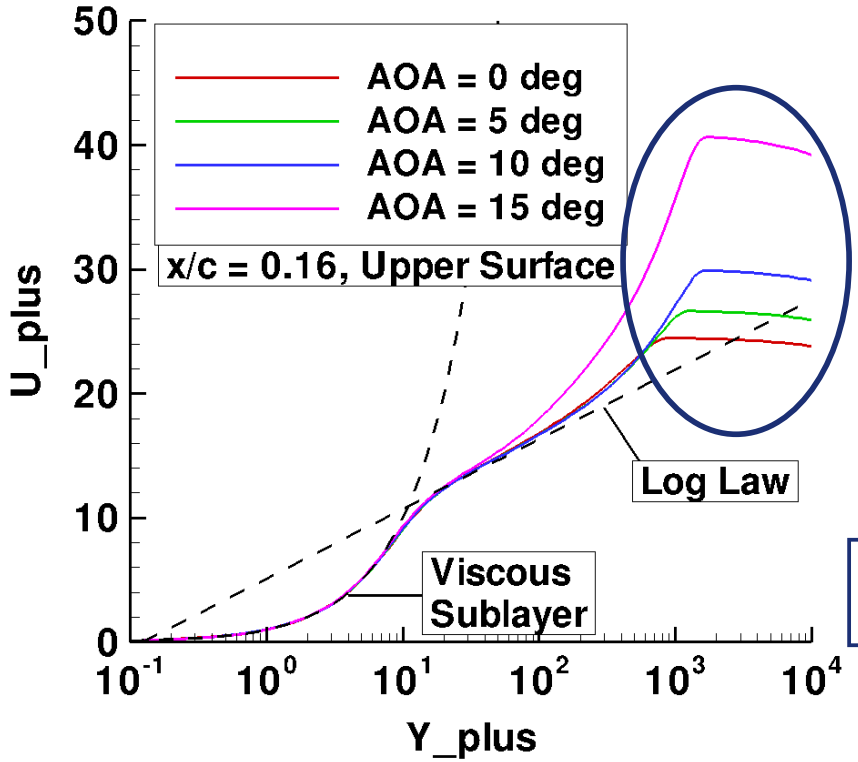




- **Poor sensitivity of linear Eddy viscosity based turbulence models to Strong Adverse Pressure Gradients (APG)**
  - **Over-production of turbulence leads to delayed flow reversal and separation**



Boundary Layers in Strong Adverse Pressure Gradients



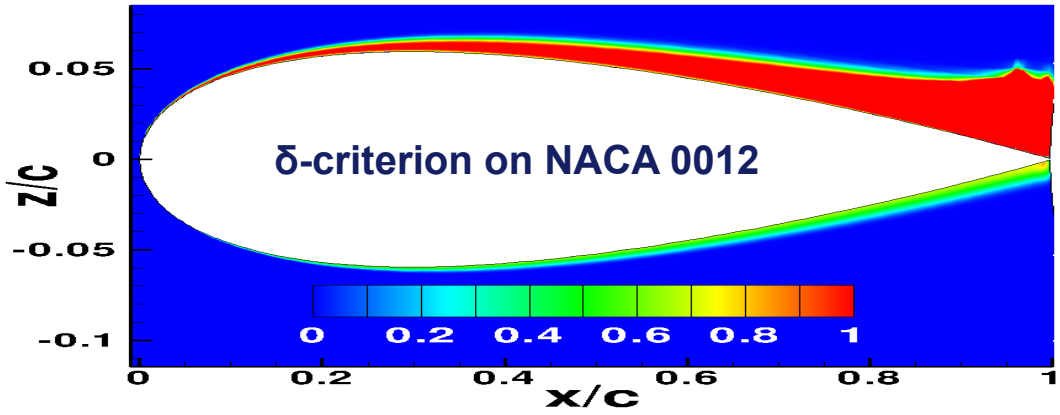
NACA 0012, Re = 6×10^6

- Viscous sublayer & Log-layer not affected under APG
- Strong pressure gradients affect outer layer
  - Outer layer profile does not collapse under non-zero pressure gradients

APG-sensitive Turbulence Modeling (Medida, 2013)

Traditional defect law valid only if $\delta = \dfrac{\mu_t \left| S_{ij} \right|}{1.5 \left| \tau_w \right|} \leq 1.0$ **, (Perry, 1973)**

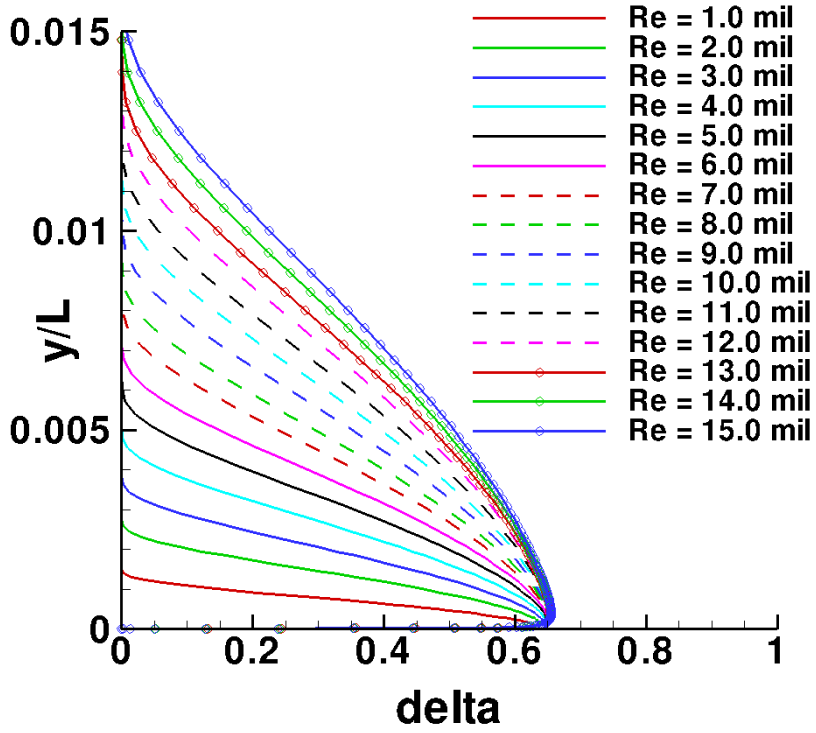
Ratio of [Local Turbulent Stress] to [Wall Shear Stress] < 1.5



Re = 6x10^6, AoA = 10°

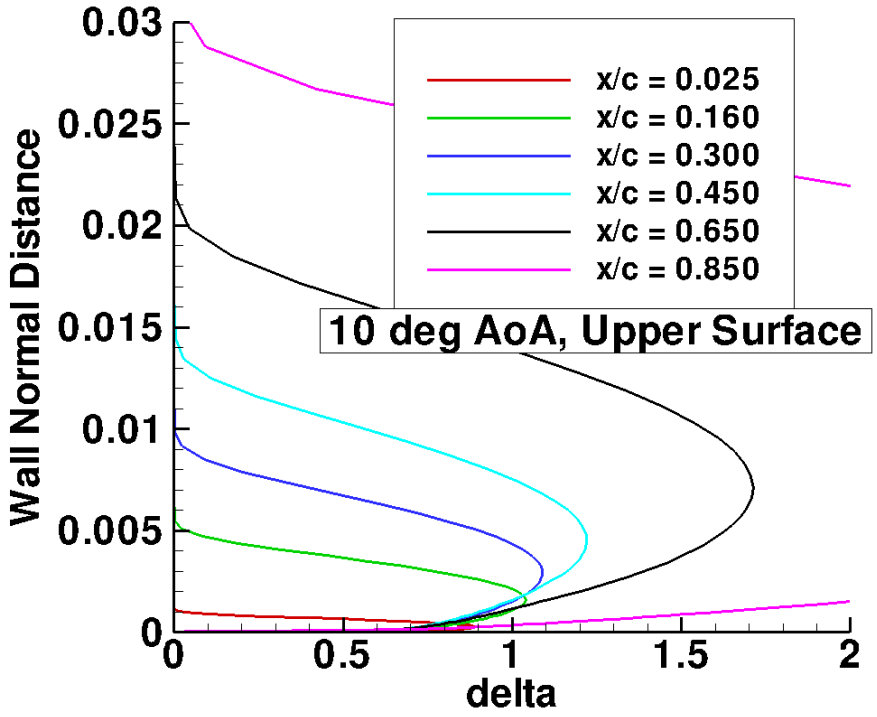
APG-sensitive Turbulence Modeling (Medida, 2013)

Traditional defect law valid only if $\delta = \dfrac{\mu_t \left| S_{ij} \right|}{1.5 \left| \tau_w \right|} \leq 1.0$ **, (Perry, 1973)**

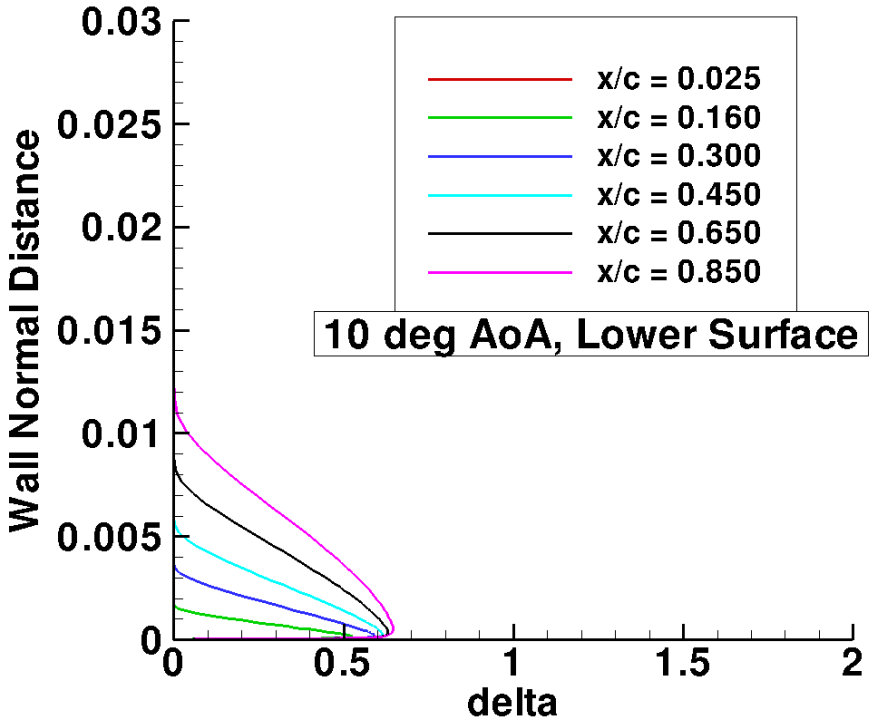


δ-criterion on zero-pressure gradient flat plate does not cross 1.0

APG-sensitive Turbulence Modeling (Medida, 2013)



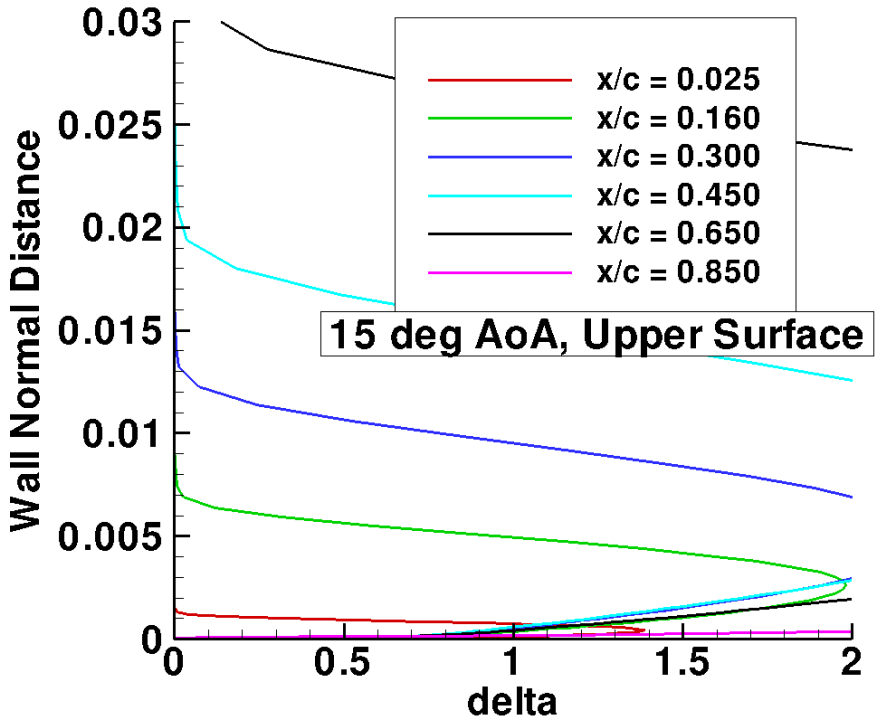
APG on Upper Surface



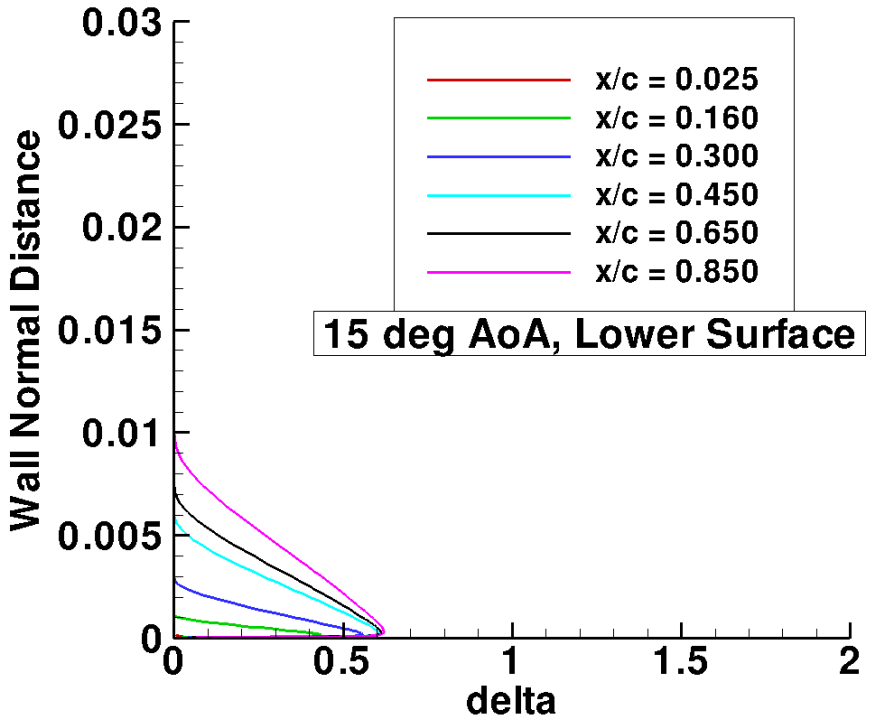
FPG on Lower Surface

δ-criterion on NACA 0012, AoA = 10°, Re = 6x10^6

APG-sensitive Turbulence Modeling (Medida, 2013)



APG on Upper Surface



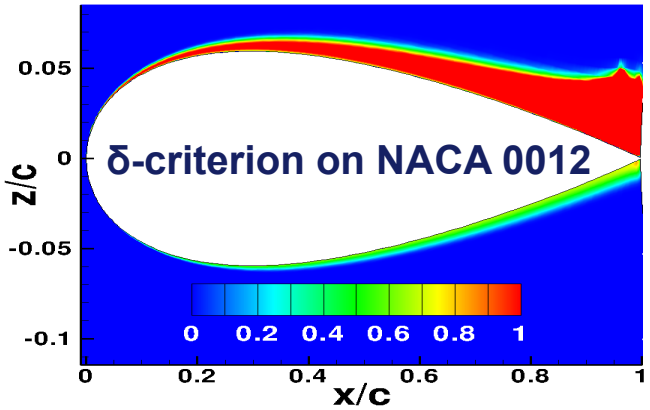
FPG on Lower Surface

δ-criterion on NACA 0012, AoA = 15°, Re = 6x10^6

APG-sensitive Turbulence Modeling (Medida, 2013)

Traditional defect law valid only if $\delta = \dfrac{\mu_t \left| S_{ij} \right|}{1.5 \left| \tau_w \right|} \leq 1.0$ **, (Perry, 1973)**

δ-criterion indicative of strong APG



Re = 6x10^6, AoA = 10°

- **Spalart-Allmaras model calibrated separately for each layer**
  - **Modified defect layer damping function based on δ-criterion**

$$r = \frac{\tilde{\nu}}{\tilde{\Omega}\alpha^2 d^2}$$

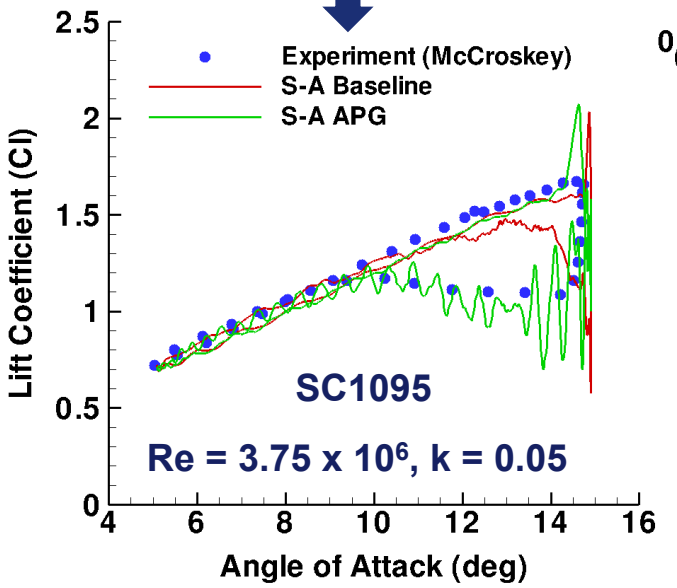
$$\alpha = \kappa - 0.15\beta, \quad \beta = \min(\max(\delta^8 - 1, 0.0), 1.0)$$

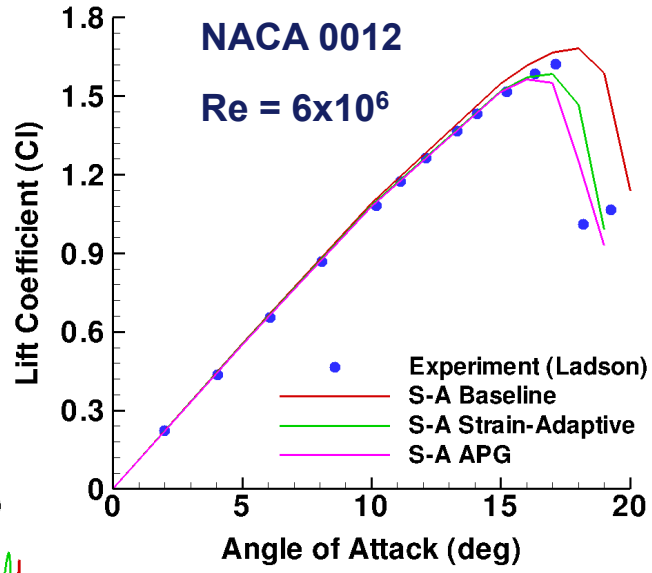
  - **Decrease value of "von Karman constant", only to improve turbulence model sensitivity**

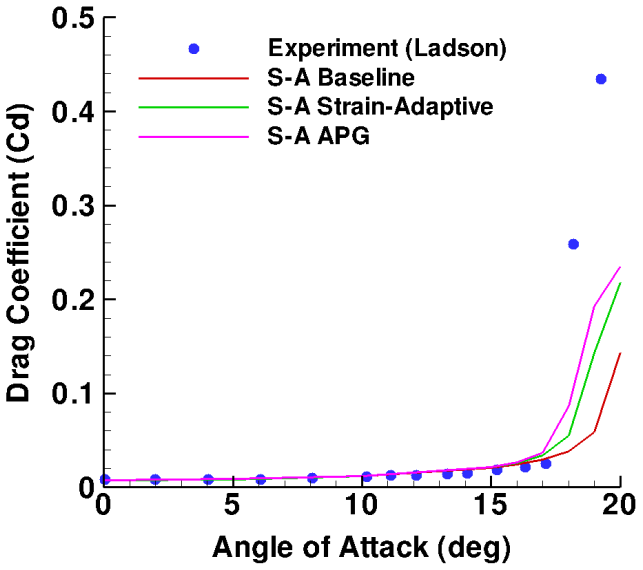
2-D Static & Dynamic Stall Prediction

Static Stall →

Dynamic Stall ↓



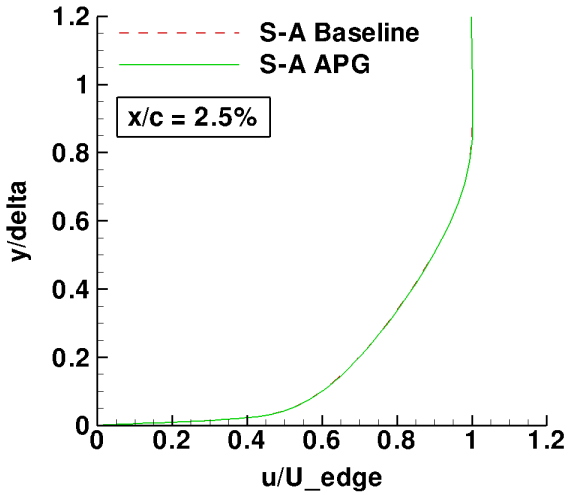


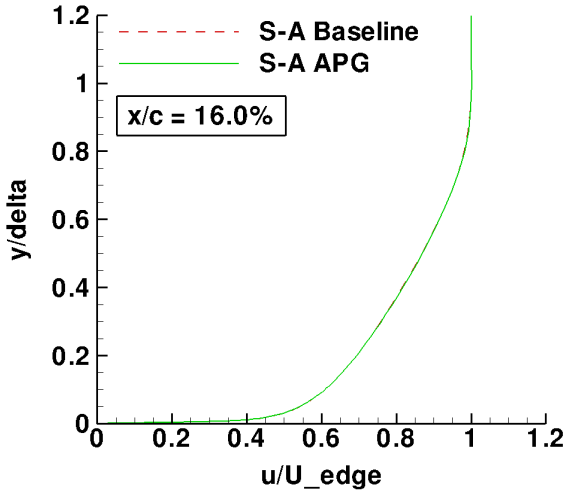


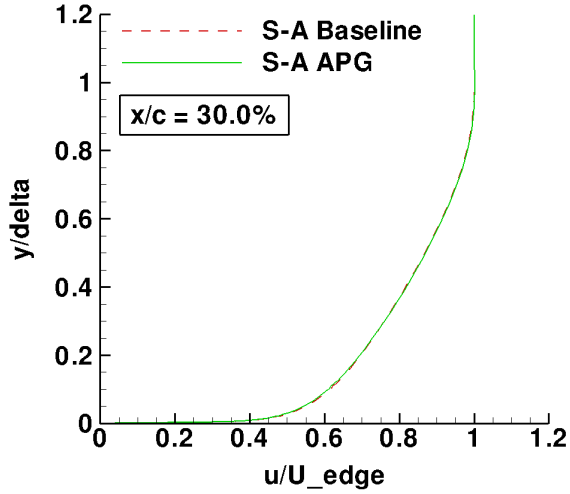
APG-modification reduces turbulence production in strong APG cases, thus allowing the boundary layer to separate earlier

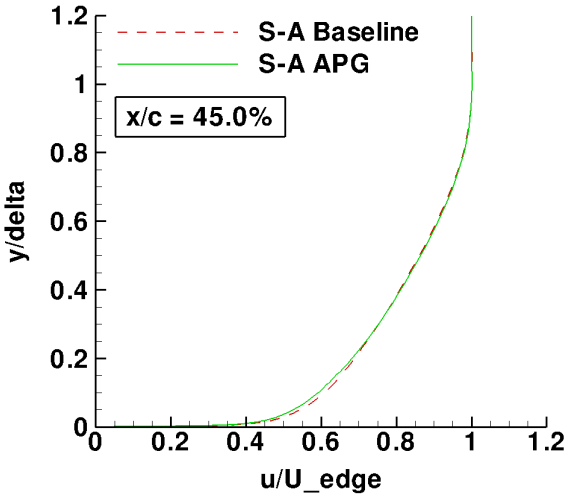
Tests on thick wind turbine airfoils show moderate gains; need to improve model calibration

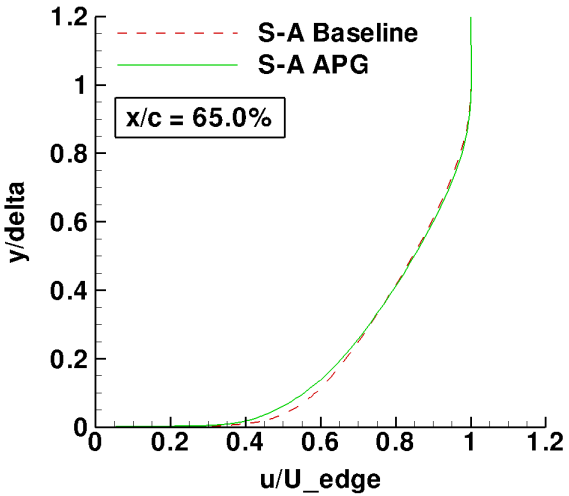
Upper Surface Velocity Profiles – NACA 0012, AoA = 10°, Re = 6x10^6

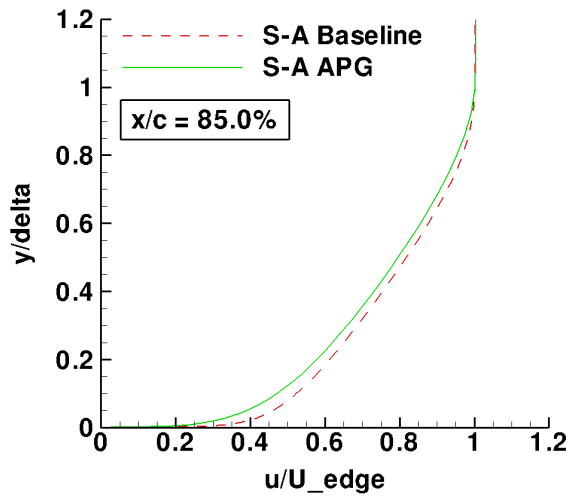




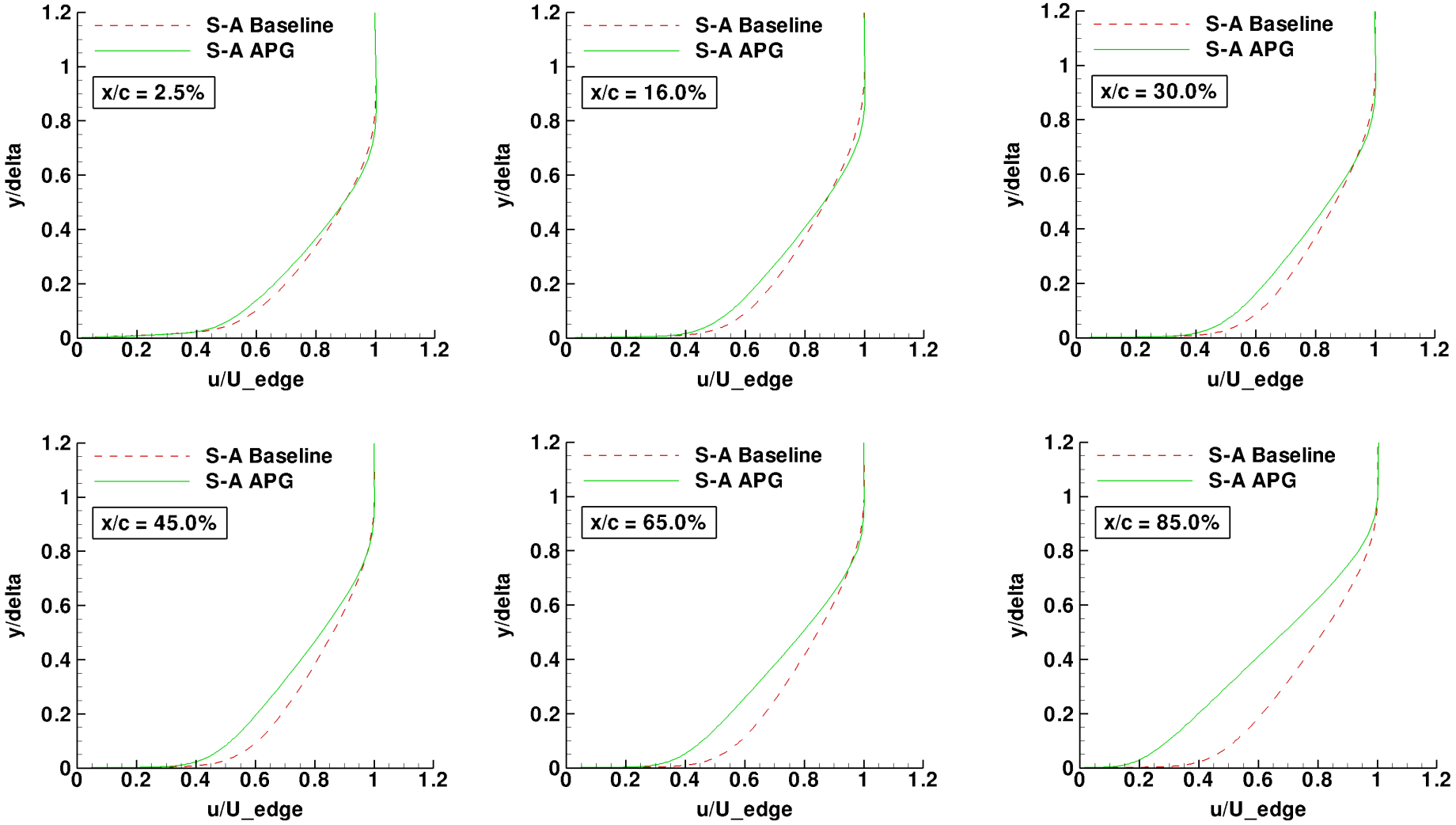




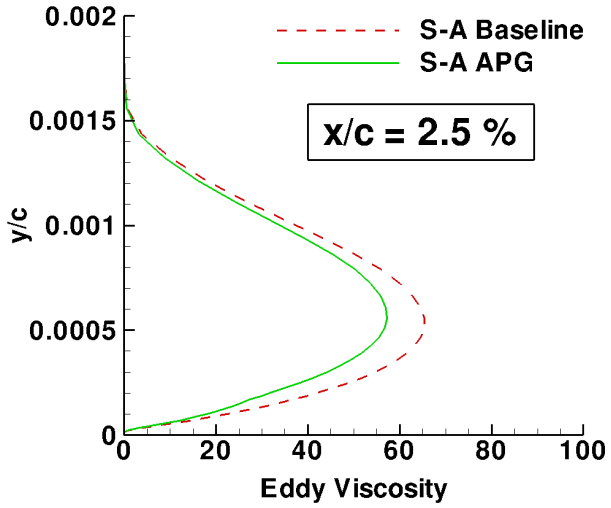


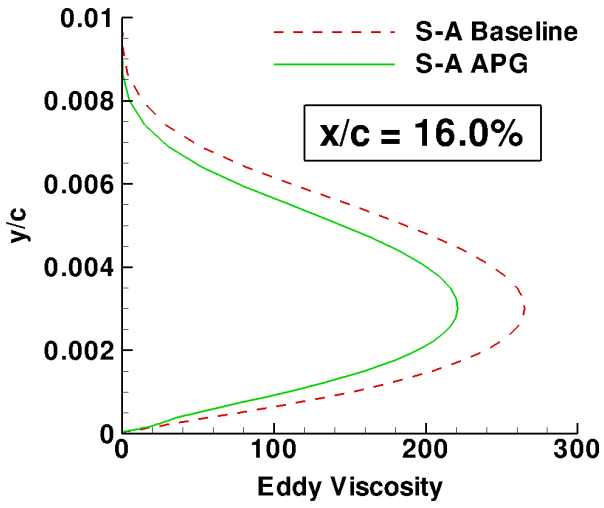


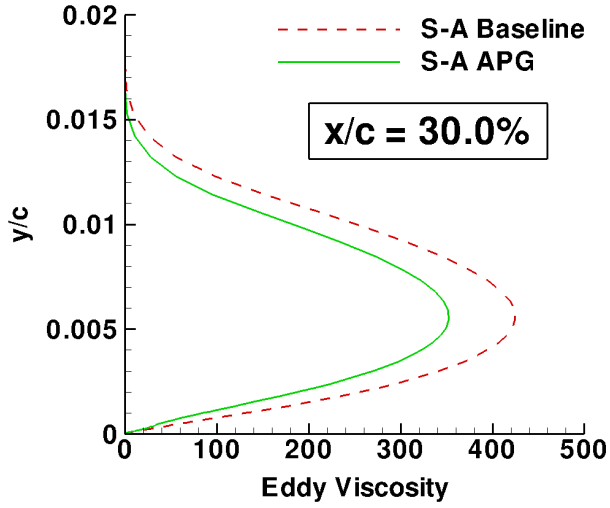
Upper Surface Velocity Profiles – NACA 0012, AoA = 15°, Re = 6x10^6

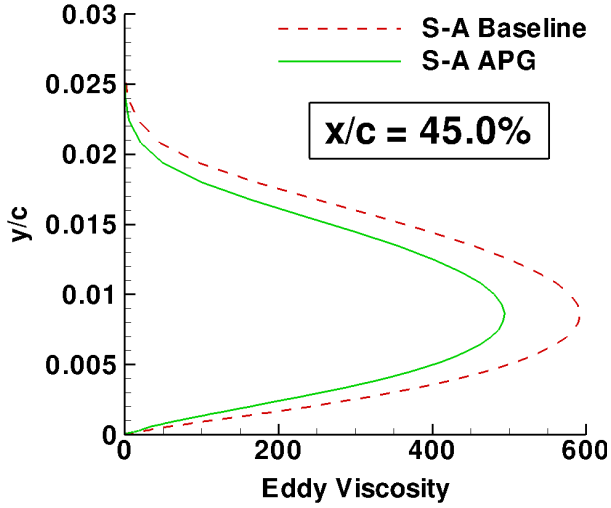


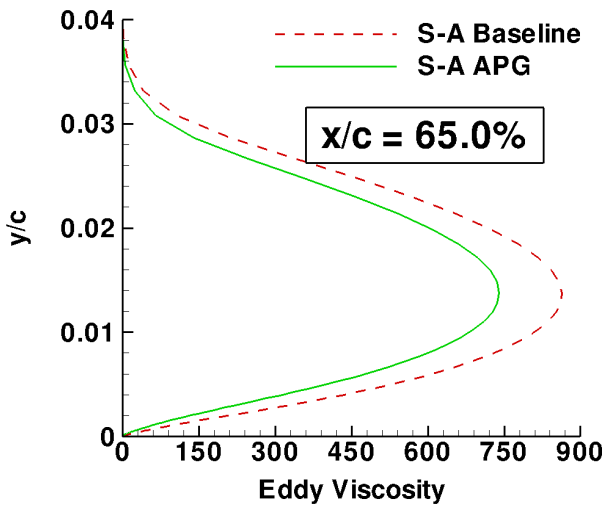
Eddy Viscosity Profiles – NACA 0012, AoA = 15°, Re = 6x10^6

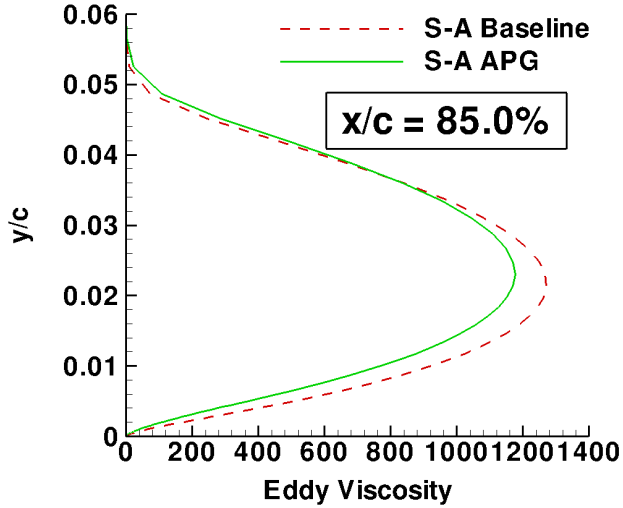




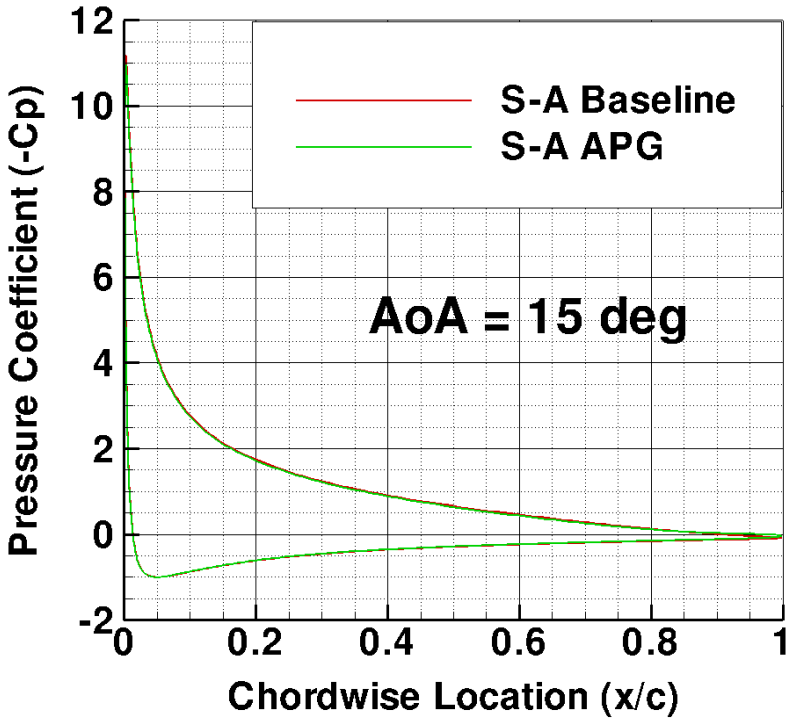


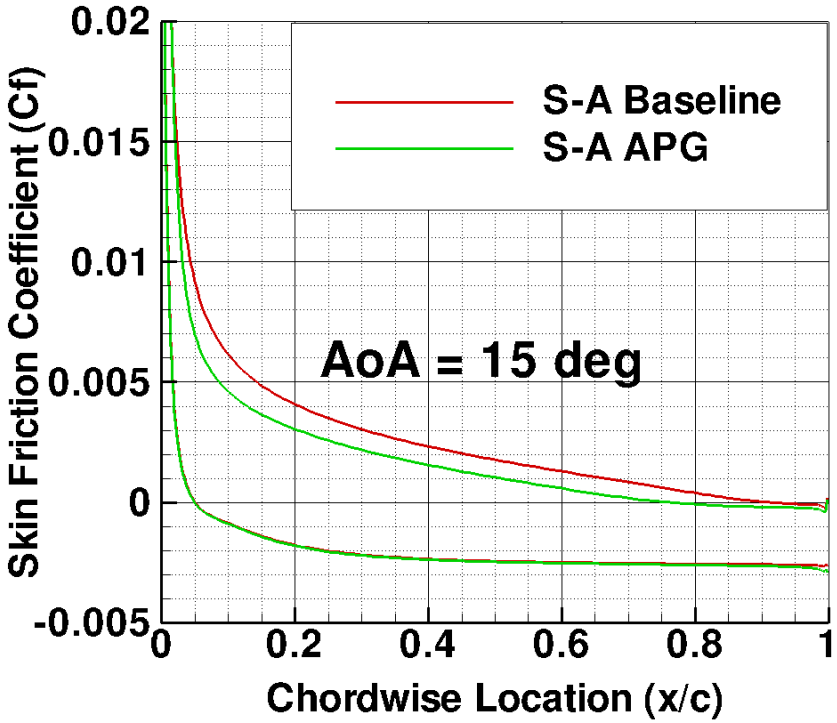






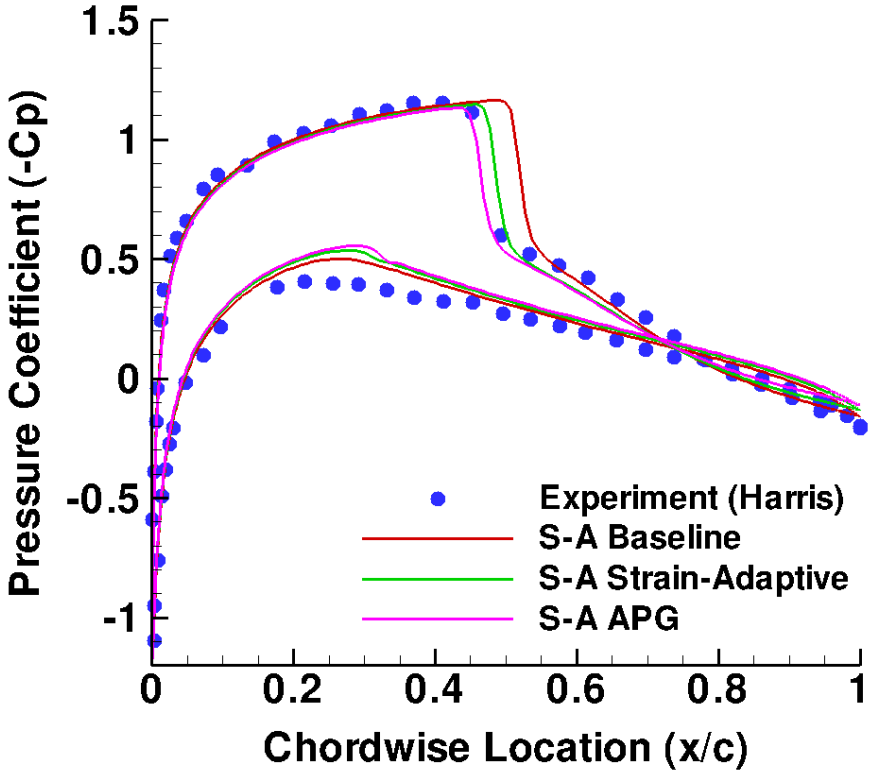
Pressure & Skin Friction – NACA 0012, AoA = 15°, Re = 6x10^6





- **S-A APG modification**
  - causes earlier separation on upper surface
  - does not alter lower surface solution

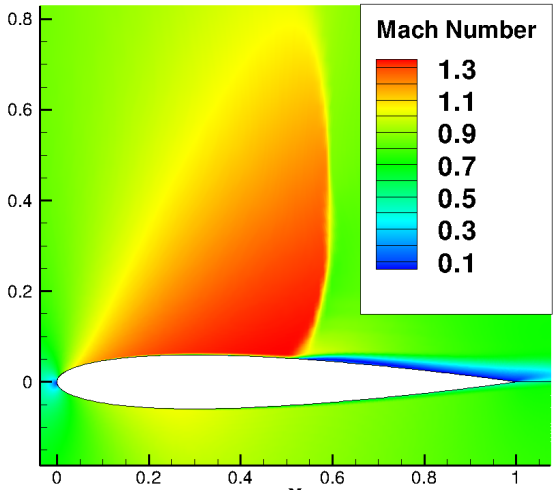
Transonic Flow w/ shock-induced separation



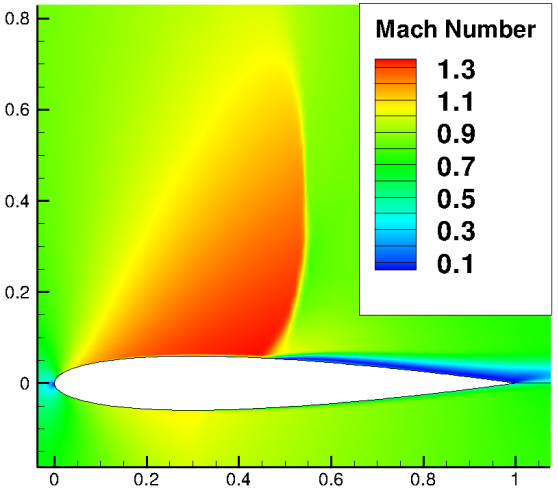
NACA 0012

M = 0.8, Re = 9 x 10^6, AoA = 2.26°

Baseline



APG



Conclusions

- Improved consistency of γ-Re_θ transition model
  - Recovered intermittency of 1.0 in turbulent boundary layer
  - Good agreement between S-A / k-ω SST models for 2-D S809 airfoil drag predictions and experimental data
- Developed new crossflow transition onset criterion for 3-D BLs
  - Improved ONERA-M6 wing 3-D transition onset prediction
  - BO 105 rotor hover simulation using γ-Re_θ transition model
    - Reduced power prediction by 2~4.5% by including transition effects
  - UH60-A offset rotor simulation – qualitative study
- Developed strong-APG sensitivity modification for RANS models
  - Reduced turbulence production in the outer layer
  - Improved 2-D static stall prediction and dynamic stall predictions

Comments

Empirical modeling is complementary to wall-modeled LES and Hybrid methods for transitional boundary layers

If Hybrid methods can resolve outer layer turbulence in the near-term, then hopefully can produce better separation predictions

Can the empirical models handle flow control scenarios?

Role of Improved Turbulence and Transition Modeling Methods in Industrial CFD Simulations

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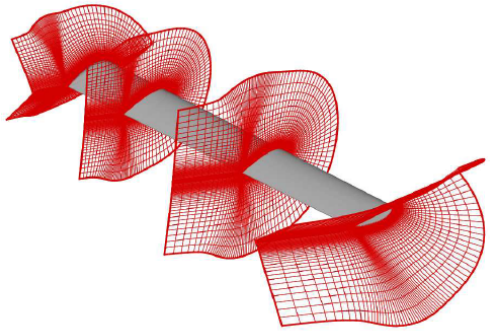
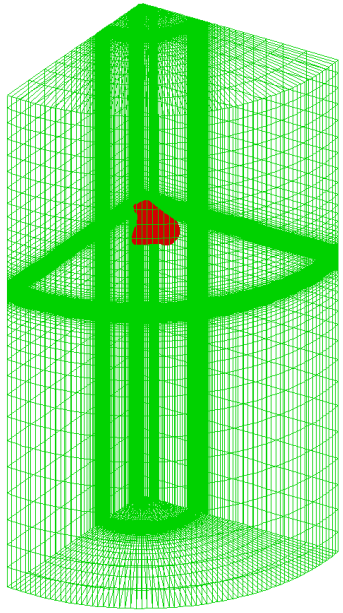
Ph.D. Candidate

Alfred Gessow Rotorcraft Center
Department of Aerospace Engineering
University of Maryland, College Park

Support: VLRCOE Grant

NIA CFD Seminar, June 11th, 2013

ADDITIONAL SLIDES

Flow Solver & Mesh System

- **OVERTURNS (UMD)**
  - Structured, Overset, Compressible, FV-RANS
  - Implicit Hole Cutting (IHC)
  - Implicit in time w/ dual-time stepping
  - Turbulence/Transition modeling
- **Structured hyperbolic mesh**
  - C-mesh topology for 2-D airfoils
  - C-O mesh topology for 3-D wings/blades
  - Overset meshes (blade-surface and wake-capture)