TICKLE
COLLEGE OF ENGINEERING

DEPARTMENT OF
MECHANICAL, AEROSPACE &
BIOMEDICAL ENGINEERING

Transitional Delayed Detached Eddy Simulation of Multielement, High-Lift Airfoils

Dr. Jim Coder
Assistant Professor

Hector D. Ortiz-Melendez
Graduate Research Assistant

Department of Mechanical, Aerospace & Biomedical Engineering

volAIR
revolutionary
Aerodynamics
Innovation and
Research

Introduction

- High-lift is a critical part of aircraft design
  - Maximum lift capability determines wing planform area
  - Wing area has leading-order effect on cruise drag
- Difficult-to-predict aerodynamic phenomena in high-lift systems
  - Laminar-turbulent transition
  - Smooth-body separation
  - Strong compressibility effects even at low flight speeds
  - Non-linear interactions between elements (c.f. A.M.O. Smith [1975])

Background

- Computational fluid dynamics often required for high-lift analyses
  - Viscous effects, compressibility, and non-linear interactions
- AIAA High-Lift Prediction Workshop (HiLiftPW) series conducted to assess current state of the art in CFD capabilities
  - Predominately RANS, with some Lattice-Boltzmann
  - RANS unable to reliably predict smooth-body separation
  - Transition modeling recognized as being influential for Trap Wing (HiLiftPW-1) and JAXA Standard Model (HiLiftPW-3) cases
  - Time accuracy may improve solution physicality

Background

- Hybrid RANS/LES Modeling
  - Extension of RANS to mitigate excessive dissipation in non-attached flows
    - Can improve prediction of flow separation
  - Delayed Detached Eddy Simulation (DDES) is widely used
  - Requires time-accurate solution on fine-resolution grids

- Transition Modeling
  - Recent developments with RANS-based models
  - Amplification factor transport model (AFT2017b) has shown promise for high-lift predictions (c.f. Coder, Pulliam, and Jensen [2018])

Desired Modeling Capabilities

- Transitional hybrid RANS/LES methods are the next progression
  - Current approaches based on γ-$Re_{\theta t}$ transition models
  - SST-based Langtry-Menter + HRLES (Hodara and Smith)
  - SA-based Medida-Baeder + DDES (Baeder et al.)

- **Goal:** Demonstrate a robust transitional DDES methodology for high-lift prediction based on SA-AFT2017b turbulence/transition modeling framework

AFT-based Transitional DDES

- SA-neg-RC model

$$\frac{D\tilde{\nu}}{Dt} = c_{b1}\tilde{S}\tilde{\nu}\left(f_{r1} - f_{t2}\right) - \left(c_{w1}f_w - \frac{c_{b1}}{k^2}f_{t2}\right)\left(\frac{\tilde{\nu}}{d}\right)^2 + \frac{1}{\sigma}\left[\frac{\partial}{\partial x_j}\left(\left(\nu + \tilde{\nu}\right)\frac{\partial \tilde{\nu}}{\partial x_j}\right) + c_{b2}\frac{\partial \tilde{\nu}}{\partial x_j}\frac{\partial \tilde{\nu}}{\partial x_j}\right]$$

- AFT2017b model

$$\frac{\partial(\rho\tilde{n})}{\partial t} + \frac{\partial(\rho u_j \tilde{n})}{\partial x_j} = \rho\Omega F_{crit}F_{growth}\frac{d\tilde{n}}{dRe_\theta} + \frac{\partial}{\partial x_j}\left[\left(\mu + \sigma_n \mu_t\right)\frac{\partial \tilde{n}}{\partial x_j}\right]$$

$$\frac{\partial\left(\rho\tilde{\gamma}\right)}{\partial t} + \frac{\partial\left(\rho u_j\tilde{\gamma}\right)}{\partial x_j} = c_1\rho S F_{onset}\left[1 - exp\left(\tilde{\gamma}\right)\right] - c_2\rho\Omega F_{turb}\left[c_3 exp\left(\tilde{\gamma}\right) - 1\right] + \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\gamma}\right)\frac{\partial\tilde{\gamma}}{\partial x_j}\right]$$

AFT-based Transitional DDES

- Intermittency growth occurs once ñ reaches N_{crit} (taken to be 9)
  - Interacts with SA model through ft2 term

$$f_{t2} = c_{t3}[1 - exp(\tilde{\gamma})]$$

- DDES uses a sensor to detect attached boundary layers

$$r_d = \frac{\nu + \nu_t}{\sqrt{U_{ij}U_{ij}\kappa^2 d^2}} \qquad f_d = 1 - \tanh\left[(8r_d)^3\right]$$

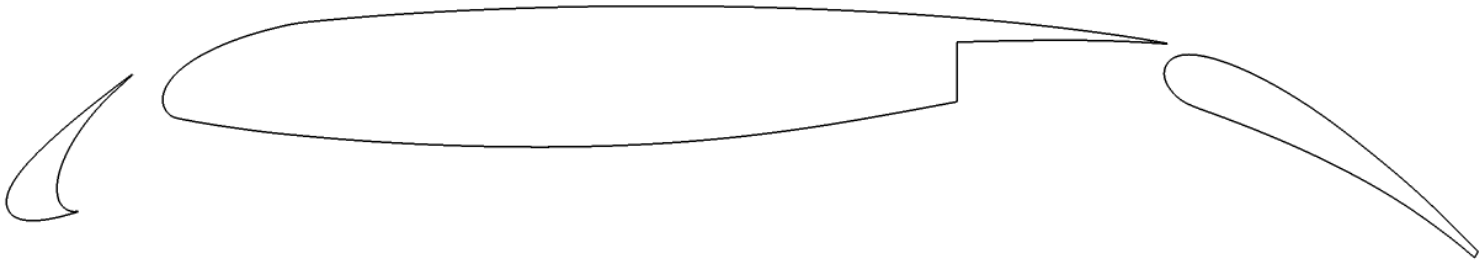
  - Extra robustness needed to account for laminar boundary layers

$$\tilde{d} = d - \min\left[\exp\left(\tilde{\gamma}\right), 1\right] f_d \max\left(0, d - C_{DES}\Delta\right)$$

Model Implementation

- SA-neg-RC-DDES-AFT2017b in NASA OVERFLOW 2.2n solver
  - Slight modifications of release version of code
- Numerical methods for current work
  - 5^{th}-order-accurate, WENO scheme (RHS) for mean flow convective fluxes
    - Upwinded Roe fluxes
  - 3^{rd}-order-accurate scheme for turbulence/transition equations
  - Implicit BDF2 temporal advancement
    - $\Delta t^* = 0.0025$
    - 15 Newton subiterations (fixed)
  - D3ADI algorithm (LHS)

Test Case – MD 30P/30N

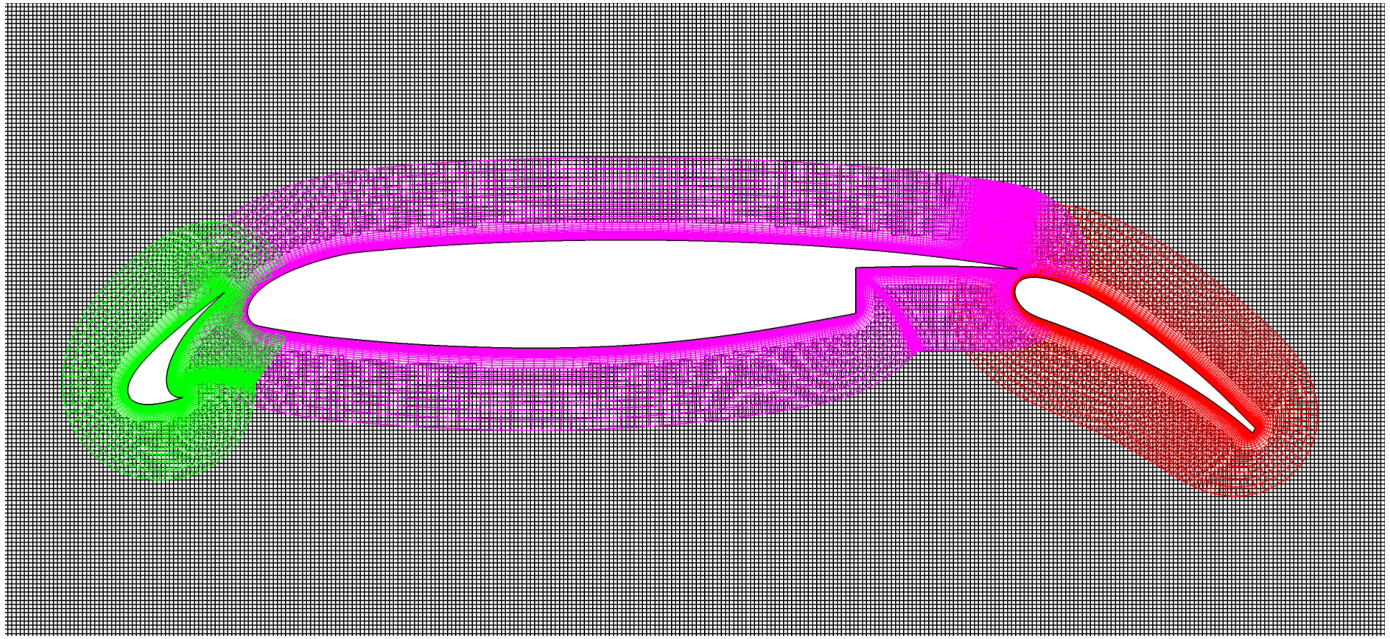


Stowed Chord	0.5588 m
Slat Deflection	30°
Slat Gap	2.95%
Slat Overhang	-2.5%
Flap Deflection	30°
Flap Gap	1.27%
Flap Overhang	0.25%

- Three-element high-lift airfoil
  - Developed by McDonnell-Douglas
  - Tested in NASA Langley LTPT
  - Available data are transitional (e.g. untripped)

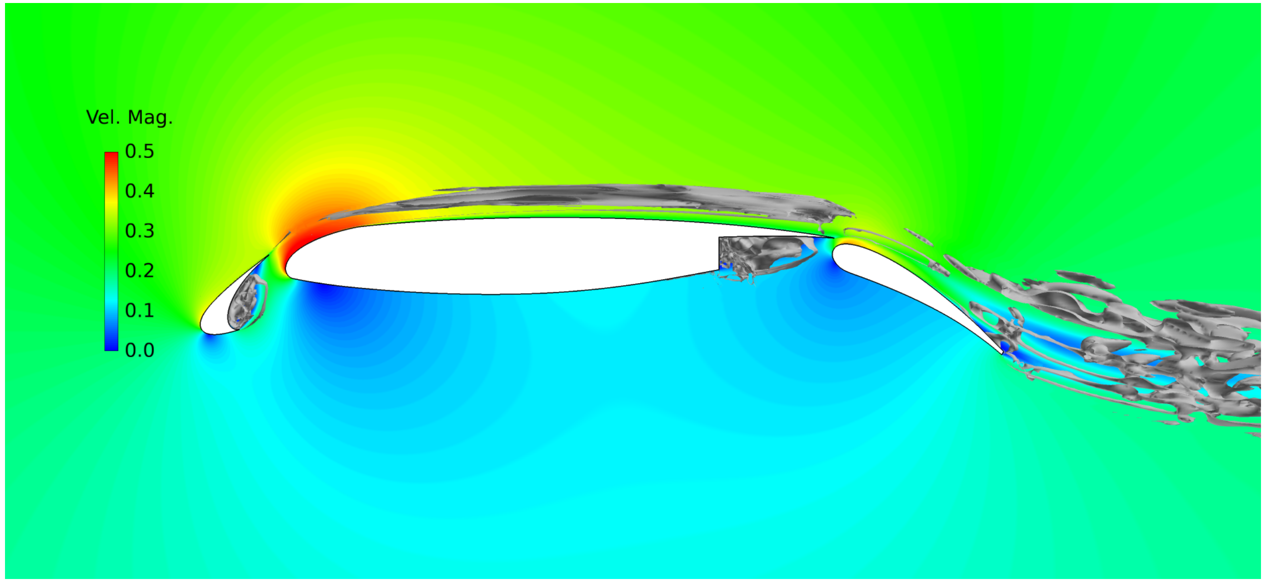
Grid System

- Overset grid system generated using Pointwise and Chimera Grid Tools
- Spanwise extent of 0.18c
  - Periodic boundaries
- Grid dimensions
  - Slat: 209x65x41
  - Main: 505x65x41
  - Flap: 205x65x41
  - **Total:** 11.7 million

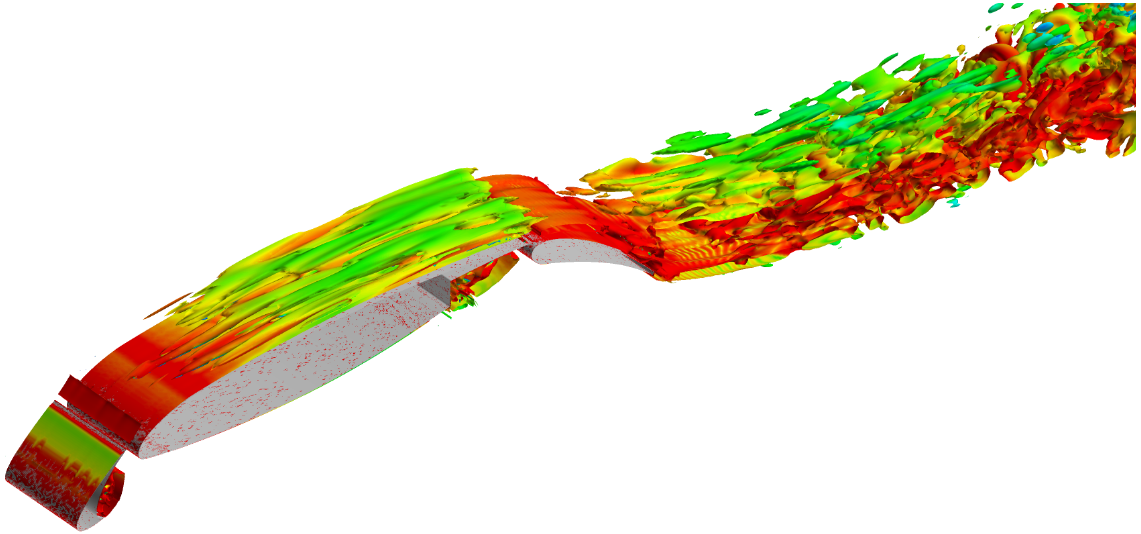


Qualitative Model Verification

- Flow Structure (α = 8°)



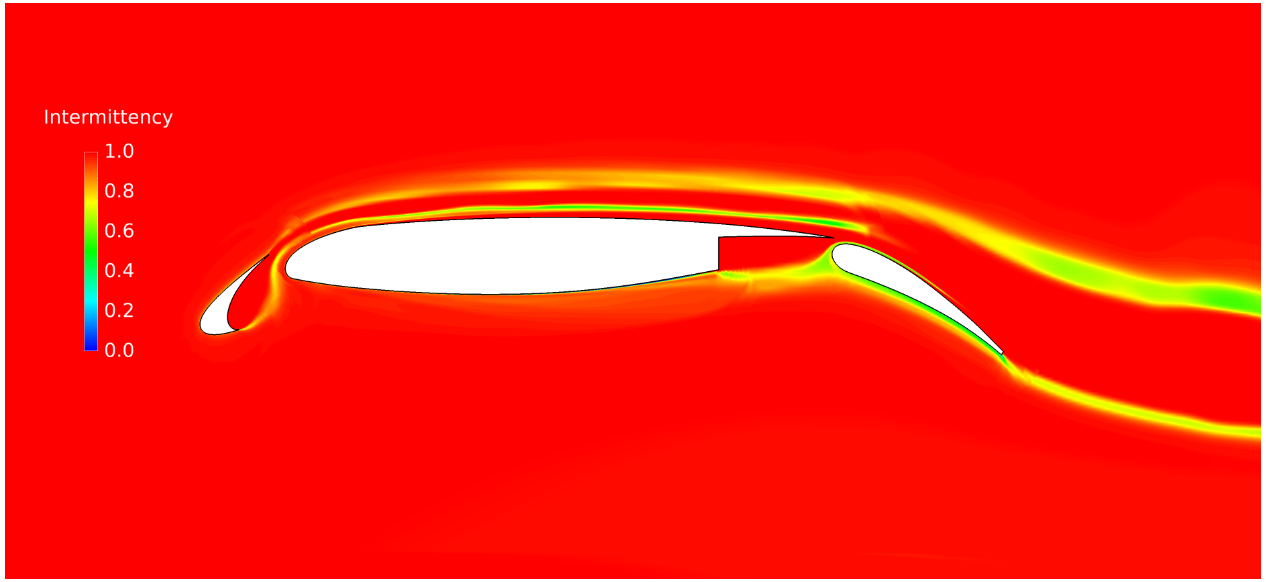
Velocity Contours with Wake Structure (Q-criterion)



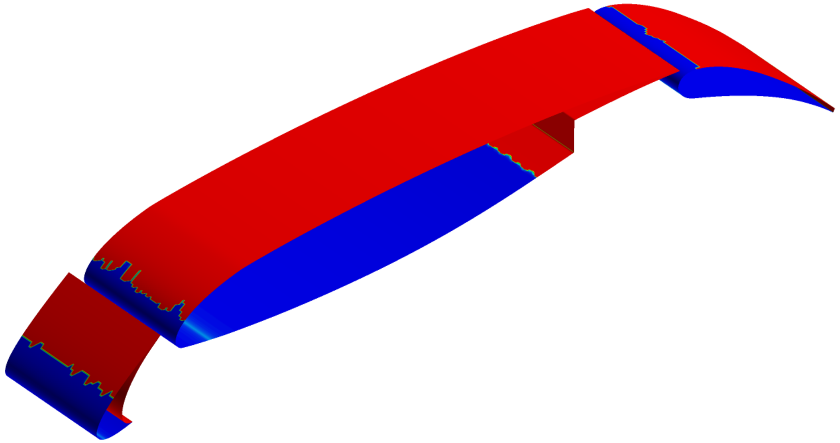
Q-criterion Isosurface (Colored by Vorticity Magnitude)

Qualitative Model Verification

- Intermittency and Transition Patterns (α = 8°)



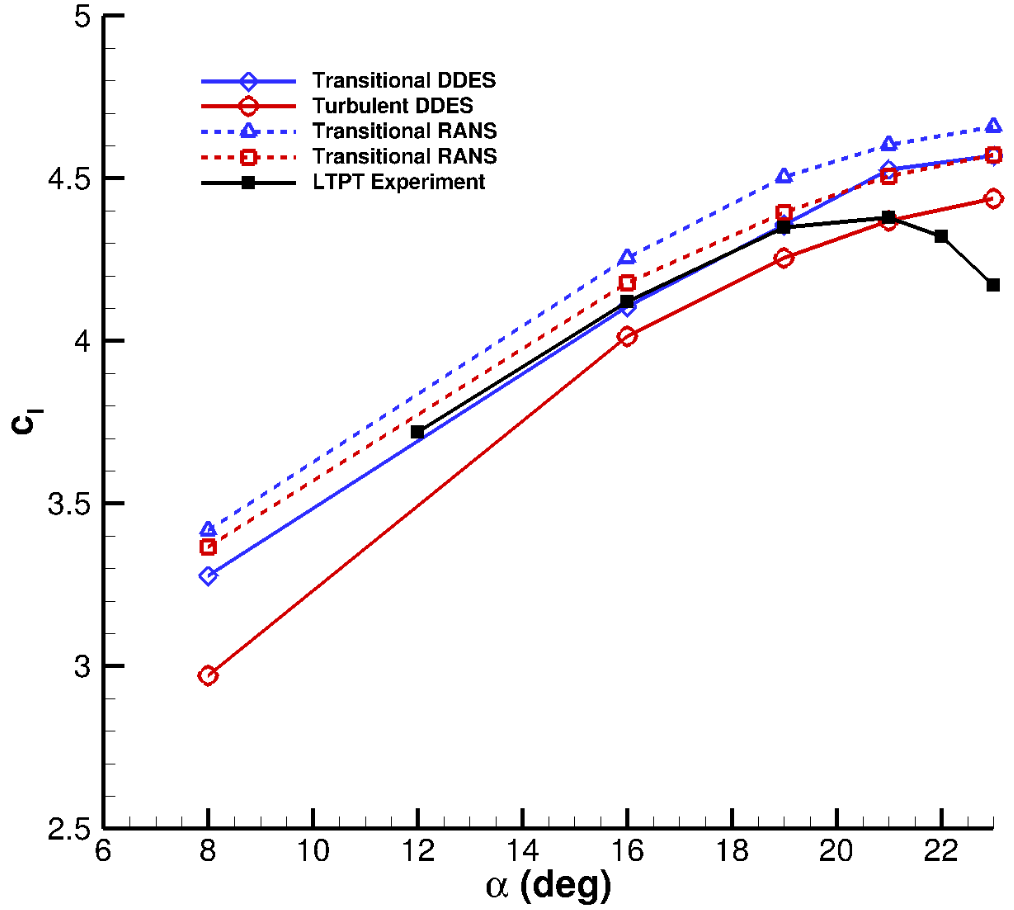
Intermittency Field



Surface Turbulence Index

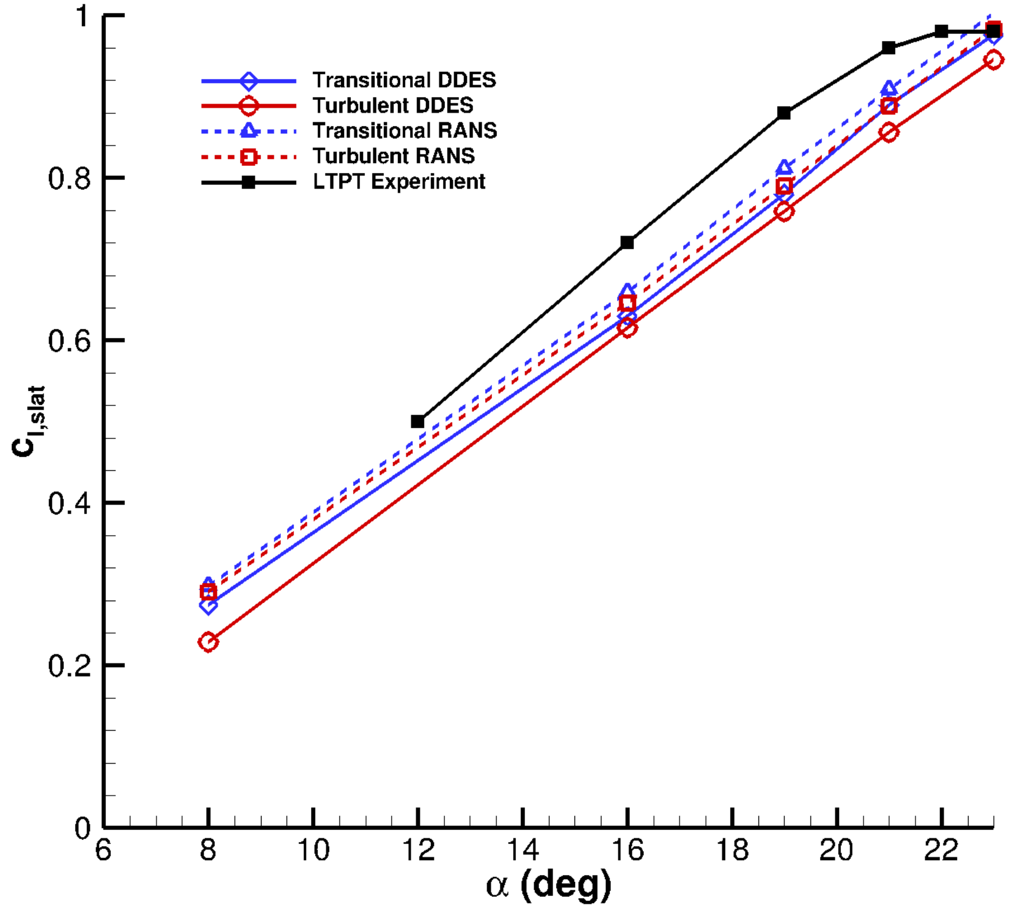
Lift Curves

- Total Lift Coefficient
  - DDES causes a decrease in lift compared to RANS
  - Transition increases lift compared to fully turbulent
  - Transitional DDES has overall best agreement, especially at lower angles
  - Stall character missed by all methods



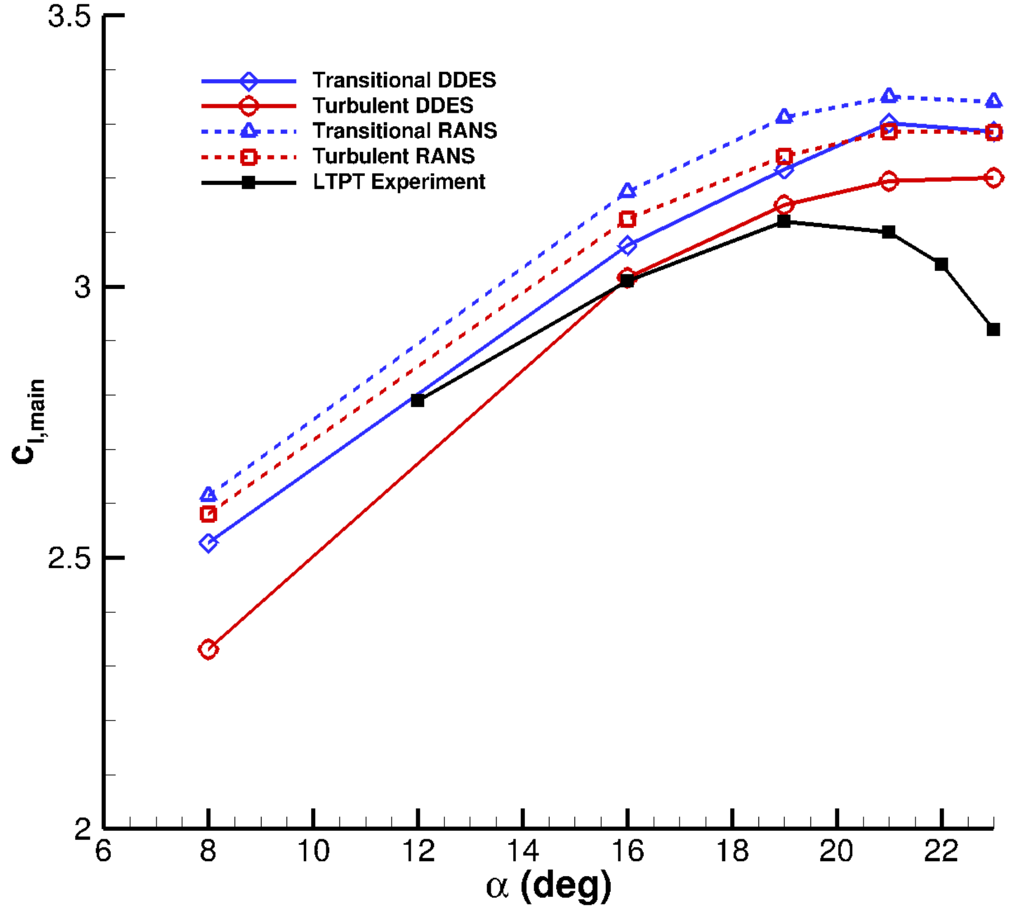
Lift Curves

- Slat Lift Coefficient
  - DDES slightly lowers the lift coefficient, and transition increases it
  - All methods fail to predict lift-curve slop at lower angles
  - None of the methods exhibit discernible stall behavior



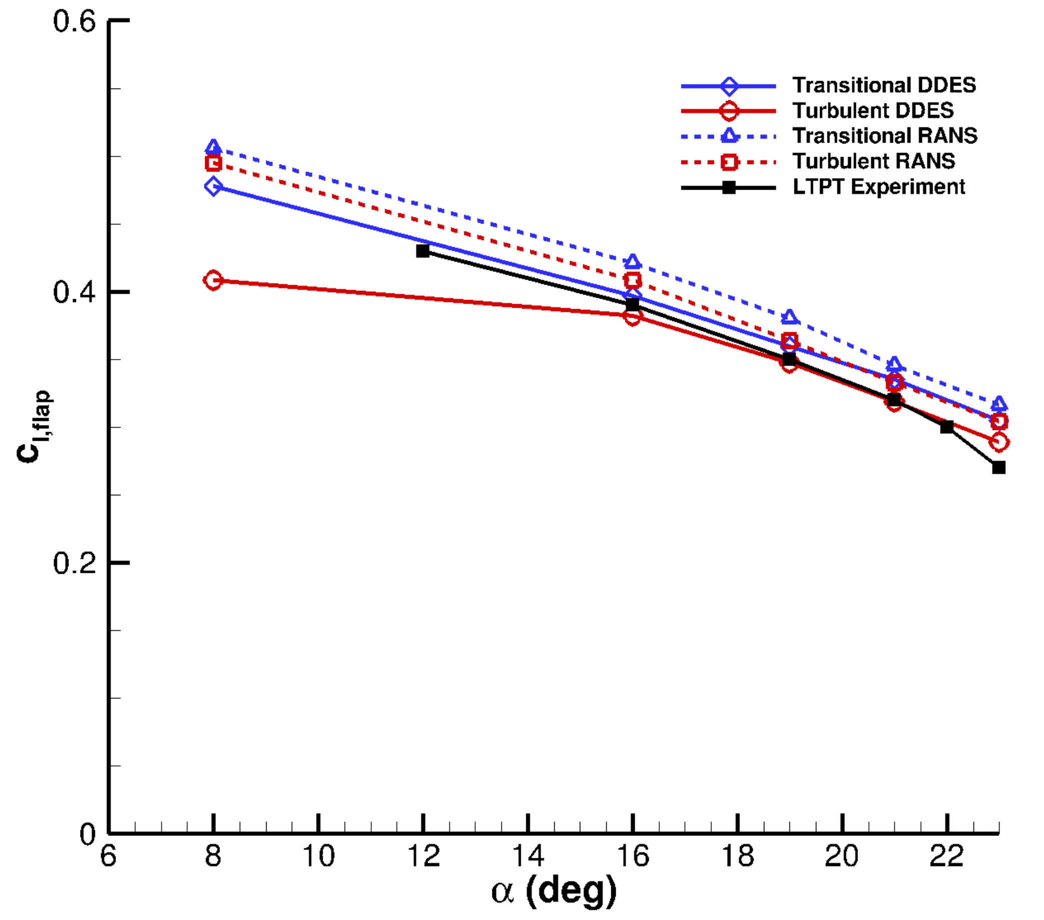
Lift Curves

- Main-Element Lift Coefficient
  - DDES lowers the lift coefficient, while transition increases it
  - Transitional DDES seems to behave better at lower angles, but overpredicts maximum lift
  - Fully turbulent DDES better at maximum lift, but not at lower angles

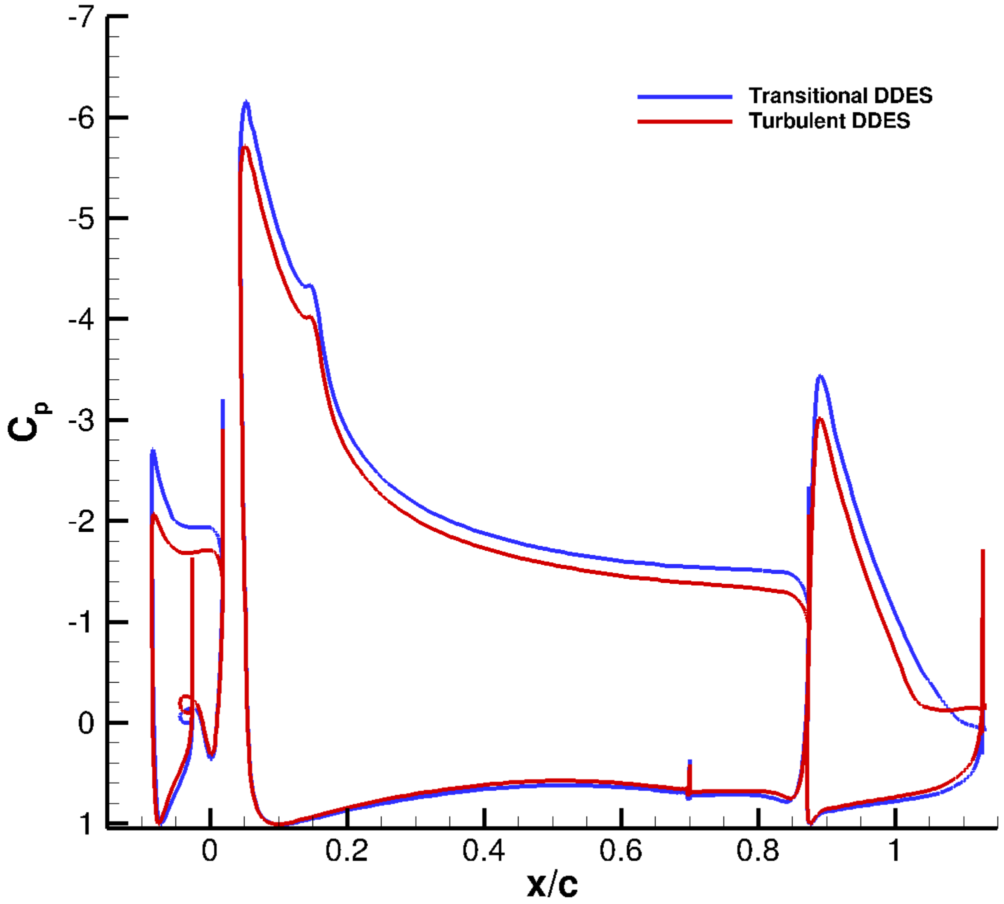


Lift Curves

- Flap Lift Coefficient
  - Transitional DDES agrees best for lower angles of attack, but does not show as much reduction in lift at higher angles

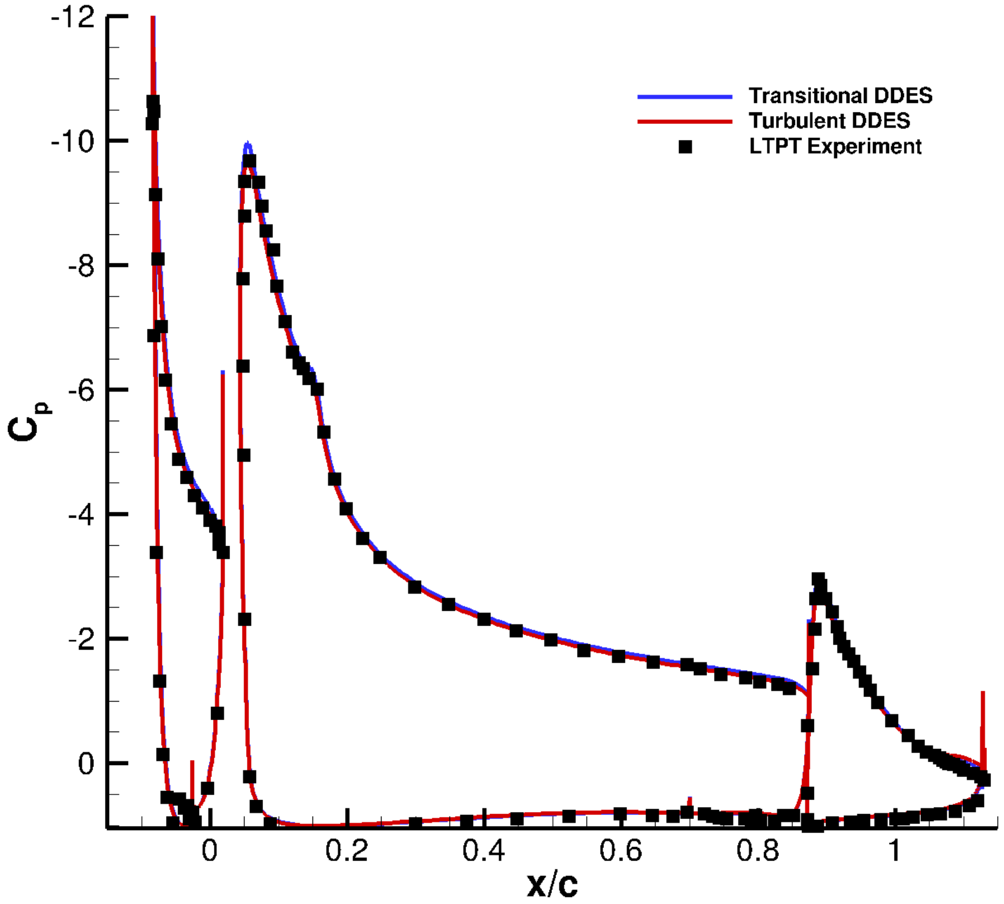


Pressure Distributions (α = 8°)



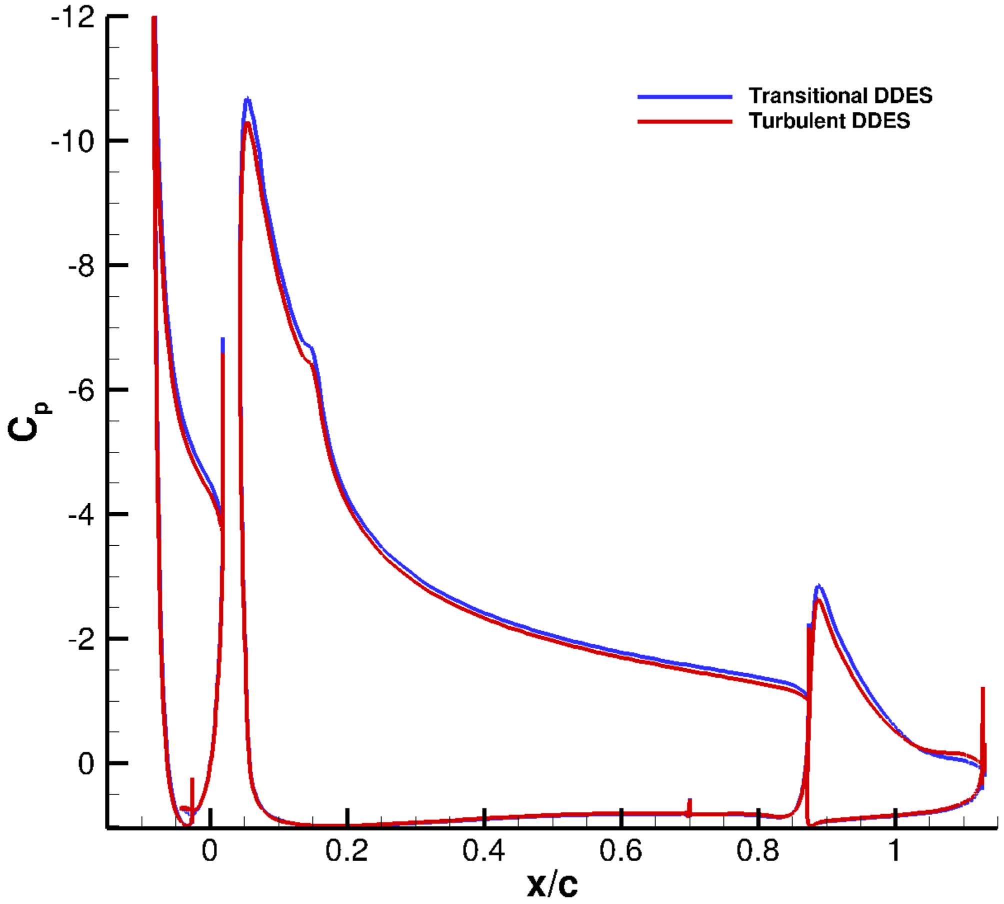
- Flap exhibits more separation in fully turbulent case
- Increased flap circulation aids main element and slat

Pressure Distributions (α = 19°)



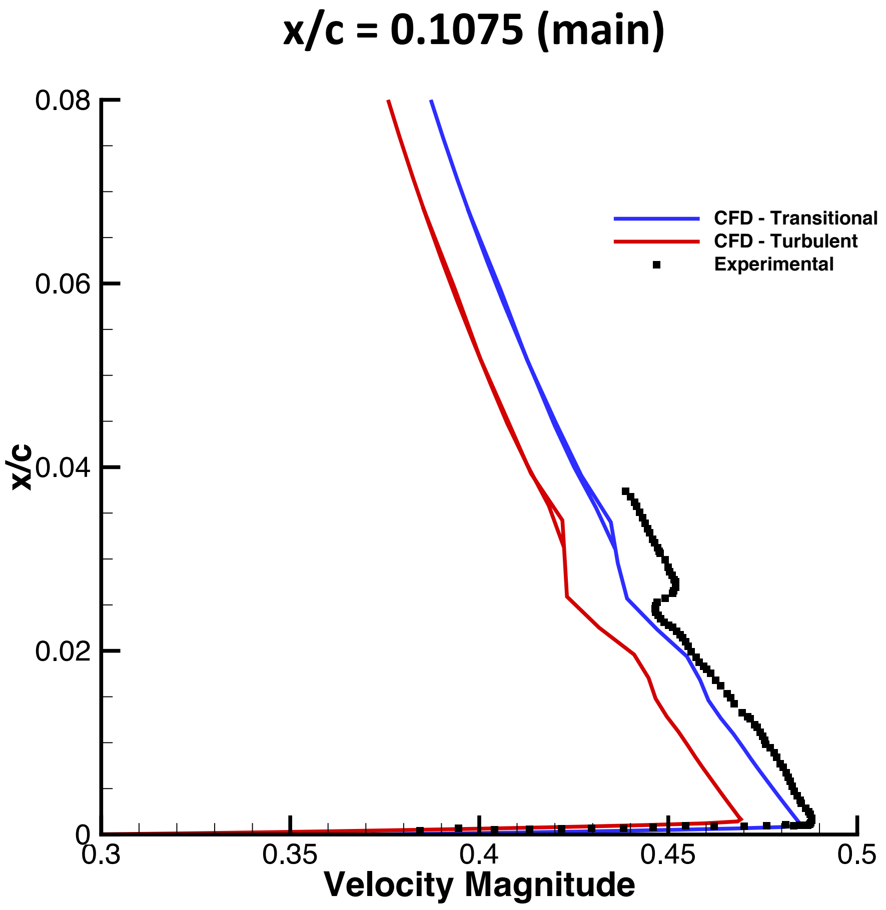
- Both transitional and turbulent agree qualitatively well with experiment
- Transitional solution agrees better for flap
- Slight difference in pressure has measurable impact on lift

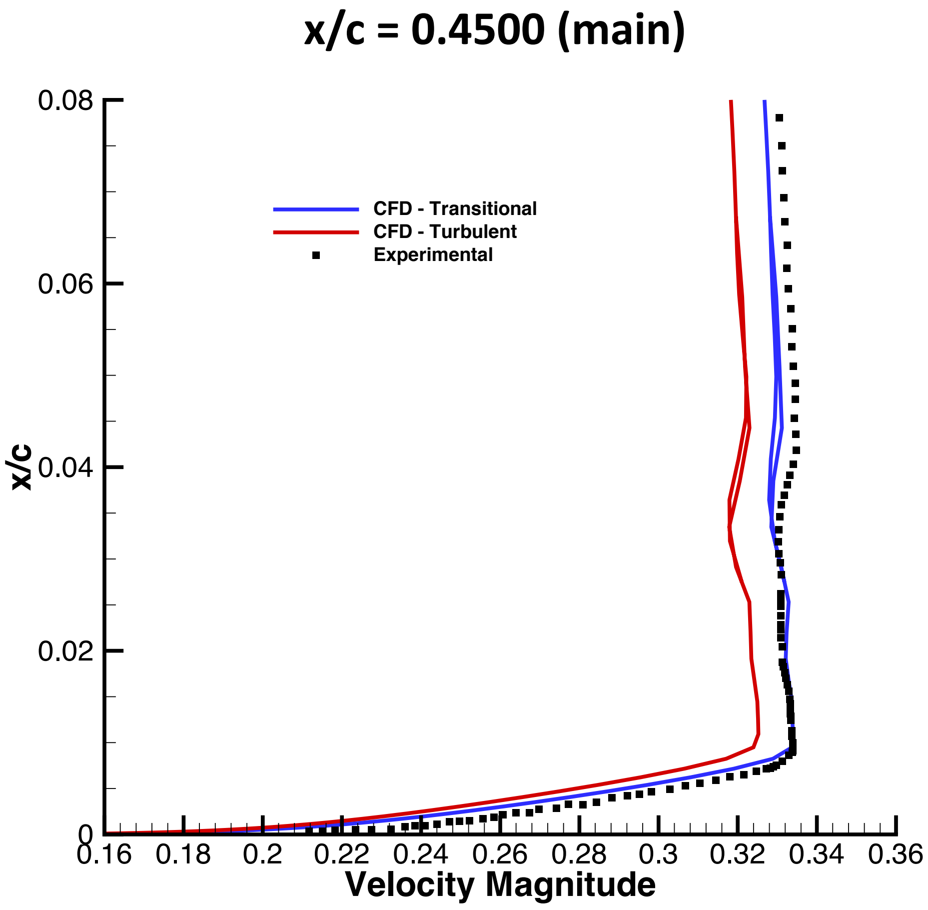
Pressure Distributions (α = 21°)



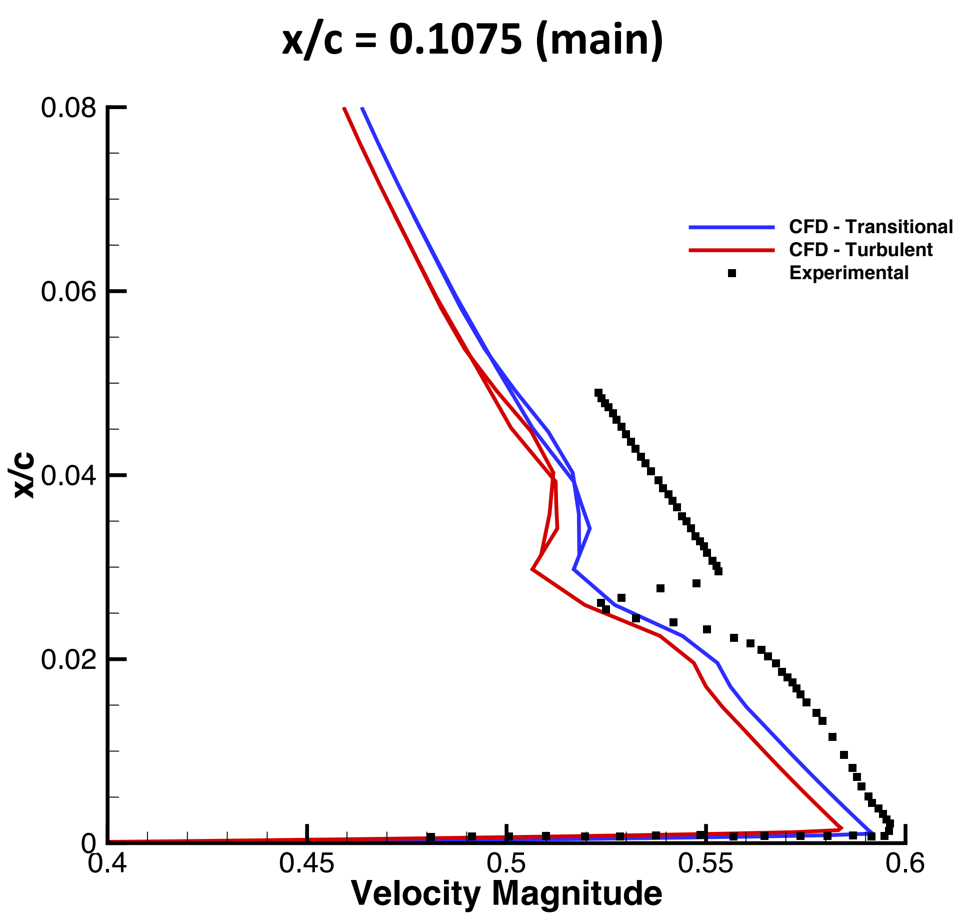
- Transitional case shows more-negative pressure peaks on flap and main element
- Less separation effects on flap with transition
- Main element not separated; however, its loading is not severe

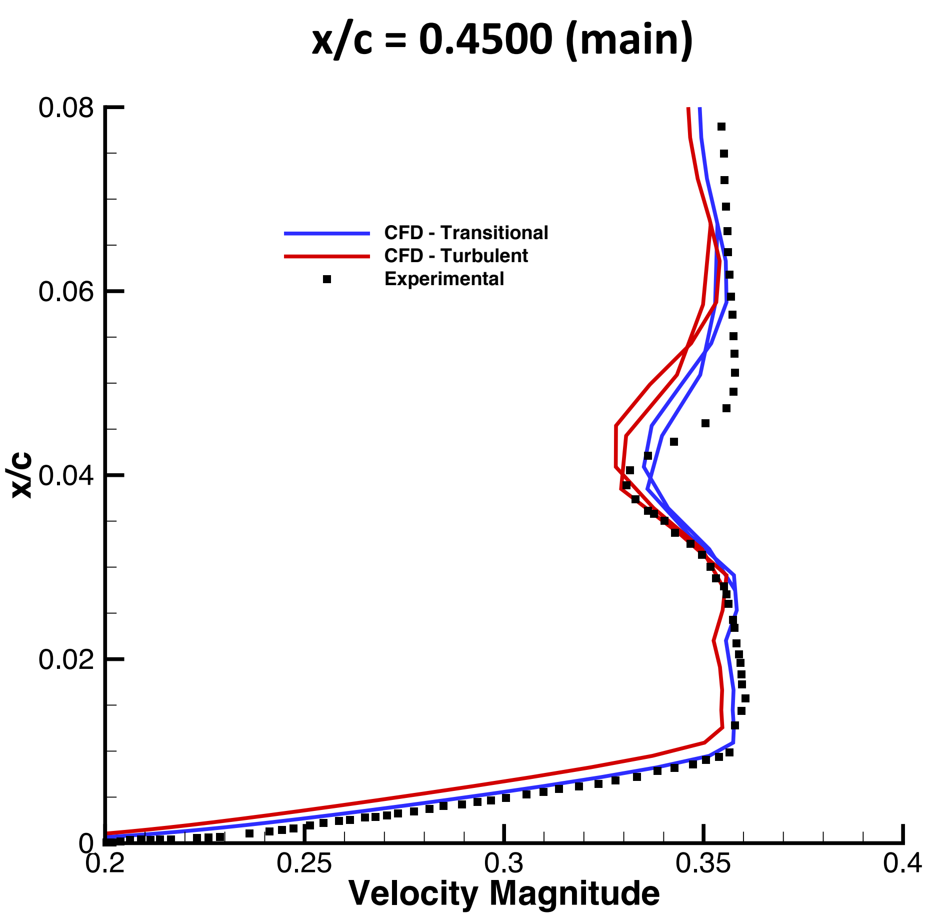
Velocity Profiles (α = 8°)



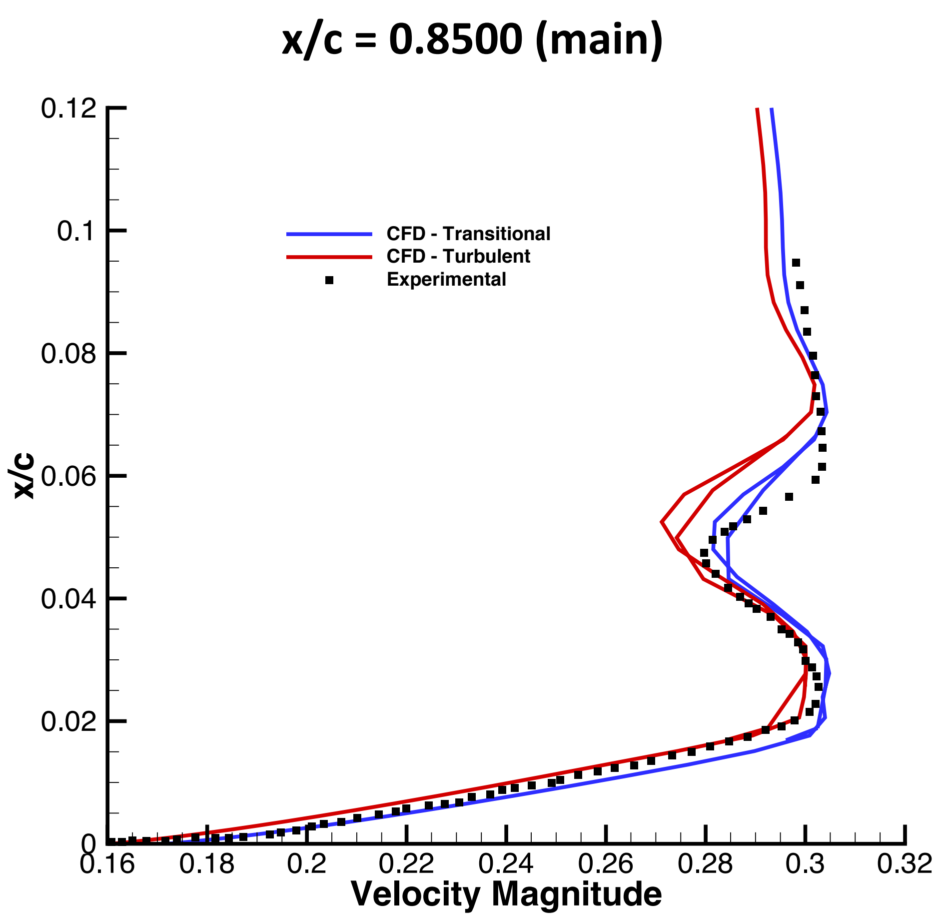


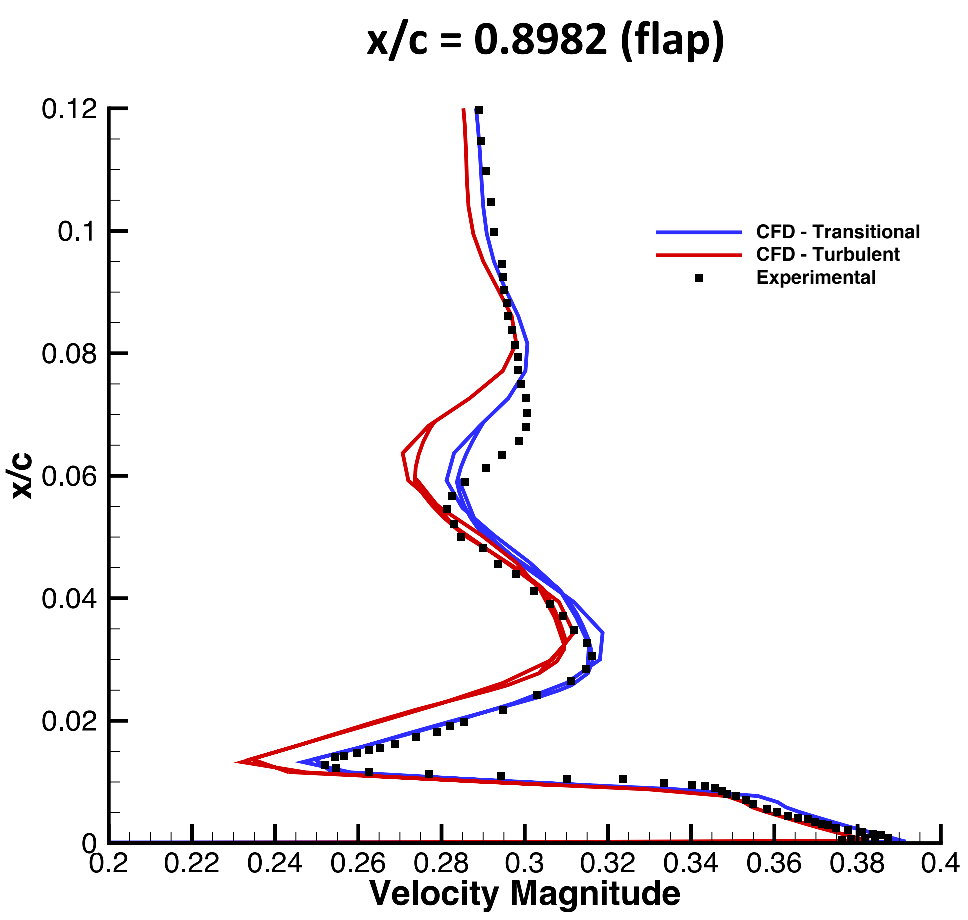
Velocity Profiles (α = 19°)





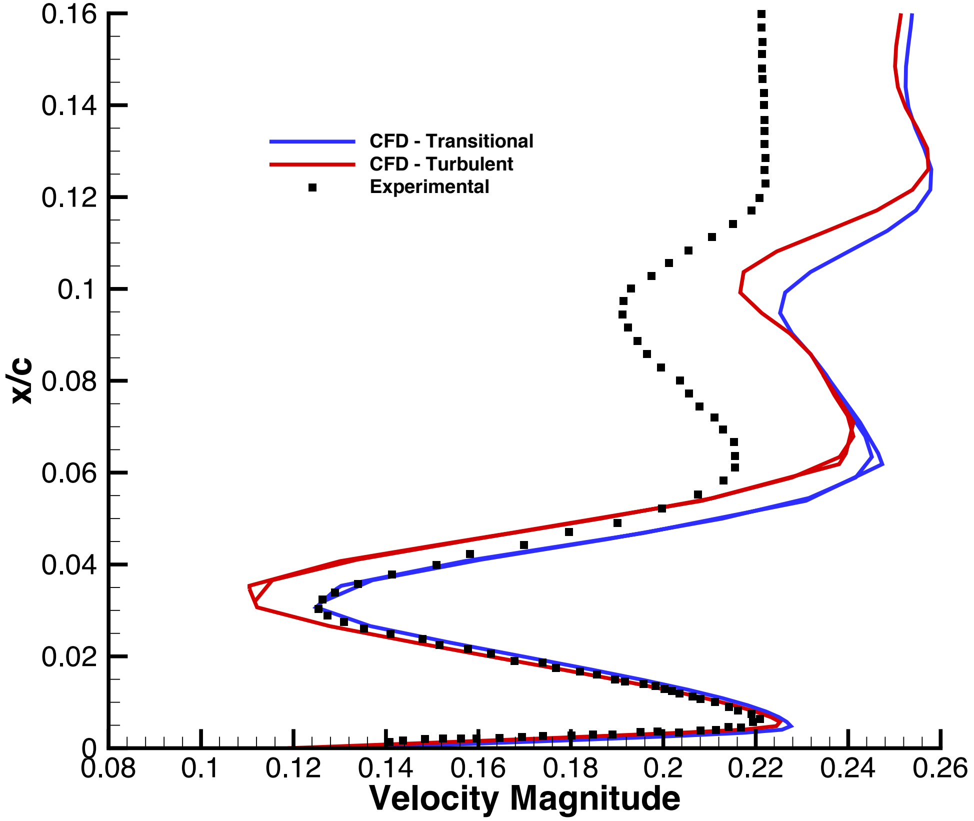
Velocity Profiles (α = 19°)



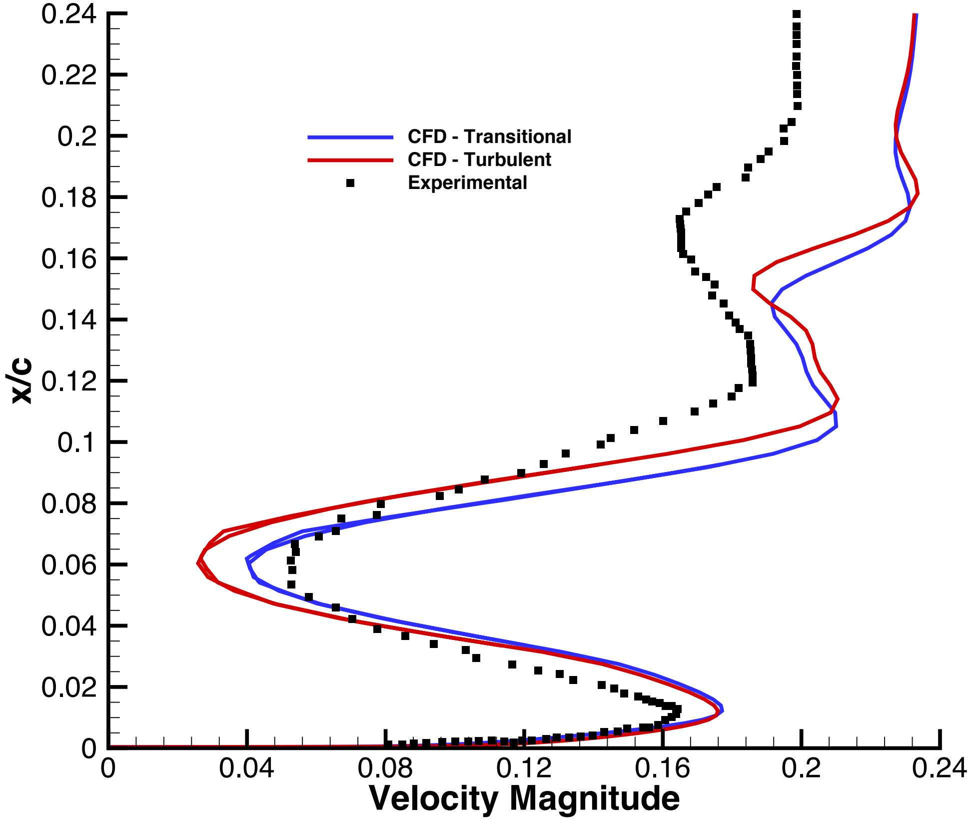


Velocity Profiles (α = 19°)

x/c = 1.0321 (flap)



x/c = 1.1125 (flap)



Conclusion

- Transitional DDES methodology established and implemented into the OVERFLOW 2.2n solver
  - Based on SA-neg turbulence model with AFT2017b transition model
  - Coupling strategy extensible to other transition models
- Consistent improvement in predictions for MD 30P/30N test case with transitional DDES over fully turbulent DDES and either transitional or turbulent RANS
  - Both integrated loads and velocity profiles
- Accurate prediction of flap loading appears to be most critical factor for this case

Acknowledgments

- This material is based upon work supported by the National Aeronautics and Space Administration (NASA) under cooperative agreement award number NNX17AJ95A (University Leadership Initiative)

Questions?