# Prediction of airfoil performance at high Reynolds numbers

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# Large Scale Wind Turbines

Increasing the rotor size may potentially lead to two obvious aerodynamic issues

- High Mach numbers in the tip region
  - Possible to avoid
  - Might be harmful for performance
- High Reynolds numbers
  - Hard to avoid
  - Might be beneficial for performance
  - Difficult to measure in controlled environment

DTU 10 MW Reference Turbine

# Airfoil performance at high Reynolds Numbers

We expect that increasing the Reynolds Number will:

- Decrease the viscous effects due to the thinning of the boundary layer
- Promote earlier transition due to increased Reynolds number

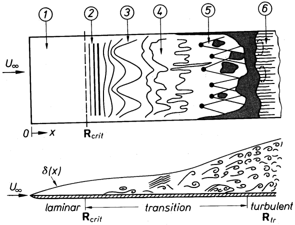
Quantification the effects can be done by:

- Measurements
  - Tunnel measurements are difficult to obtain at high Re and low M
  - Openly available data are sparse
- Computations
  - Model performance in this range is unknown

# Introduction
## Laminar turbulent transition

- The transition process depend on many parameters
  - Reynolds Number
  - Free stream turbulence level
  - Laminar separation bubbles
  - Cross flow
  - Surface roughness
  - Mass injection

- Typically approaches for transition modeling
  - $e^n$ method (Orr-Sommerfeld eqn.)
  - Empirical correlations
    - Michel
    - Mayle
    - Abu-Ghannam and Shaw
    - Suzen



# The $\gamma - Re_\theta$ Correlation based transition model

- The model is based on comparing the local Momentum Thickness Reynolds number with a critical value from empirical expressions

$$Re_\theta = Re_{\theta t}$$

- The following relation is used to simplify the computations in a general CFD code

$$Re_\theta = \frac{Re_{\nu_t max}}{2.193}$$

- The model is based on transport equations, and can easily be implemented in general purpose flow solvers
- In the present form the model handles natural transition, by-pass transition, and separation induced transition
- The transition model is coupled to the $k - \omega$ SST model through the production and destruction terms in the k-equation

# $E^n$ model for natural transition

The $E^n$ method is based on analyzing the behavior of small disturbances in the boundary layer

$$\psi(y) = \phi(y) \exp\left[i(\alpha x - \omega t)\right]$$

The disturbances are inserted in the Navier-Stokes equations, and linearized to give the Orr-Sommerfeld equation

$$(U^* - c^*)(\phi'' - \alpha^2\phi) - (u^*)''\phi = \frac{-i}{\alpha Re_\theta}(\phi'''' - 2\alpha^2\phi'' + \alpha^4\phi)$$

The Orr-Sommerfeld equation is solved with the following boundary conditions:

$$\phi(0) = \phi'(0) = 0 \text{ and, } \phi(\infty) = \phi'(\infty) = 0$$

In the EllipSys, the $E^n$ model can be used together with a bypass and a bubble criteria.

# Computational Setup
## Flow Solver

- We use the EllipSys2D incompressible solver.
- Diffusive terms by second order accurate central differences.
- Convective terms by QUICK.
- Steady state computations.
- Turbulence modeling by the $k - \omega$ SST model
- Transitional computations using $\gamma - Re_{\theta t}$ transition model and $E^n$ model
- Reynolds number [3-40] million.

# Test Cases
## Selected cases

- $NACA63-018$
- $DU00-W-212$
- $NACA64_2A015$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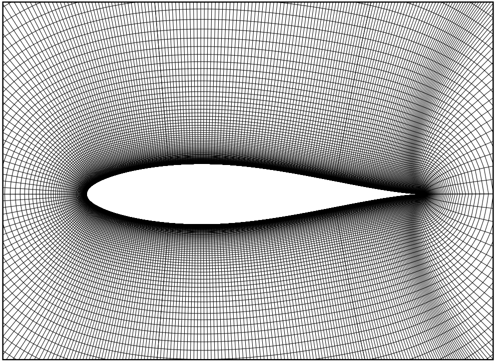
# Test Case, NACA63-018
## Computational setup

- Airfoil computations for Re=[3, 9, 20] million
- Using three transition models, $E^n$, $E^n$ + BP and $\gamma - Re_\theta$
- For natural transition we assume (N=9)
- Mesh resolution 384 $\times$ 256

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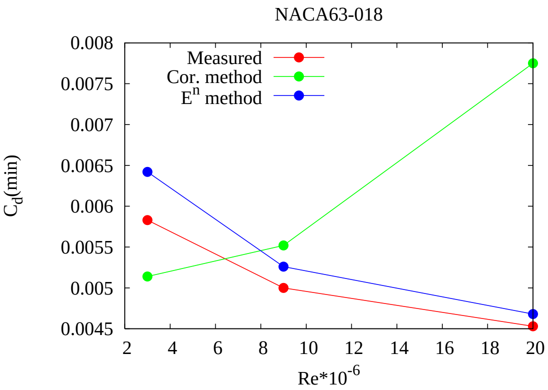
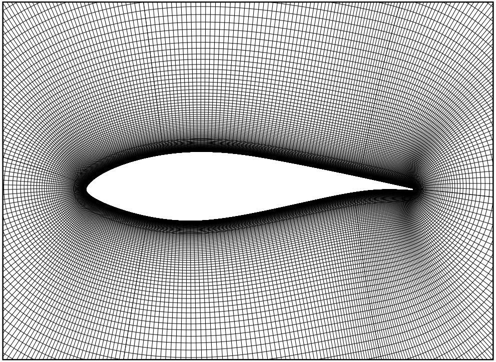
# Performance for varying Re



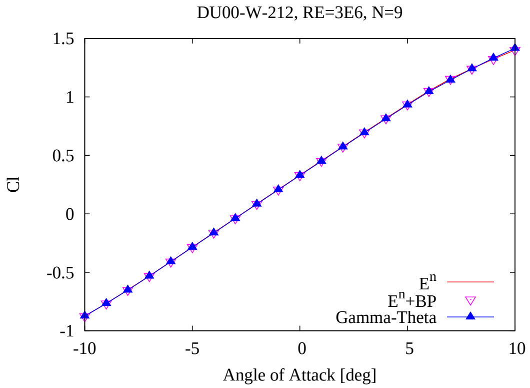

The correlation based model do not respond correctly to varying Re !

## Computational set-up

- Airfoil computations for Re=[3, 9, 15] million
- Using three transition models, $E^n$, $E^n$ + BP and $\gamma - Re_\theta$
- All assuming natural transition (N=9)
- Mesh resolution 384 $\times$ 256



# Test Case, DU00-W-212
## Lift, Natural Transition





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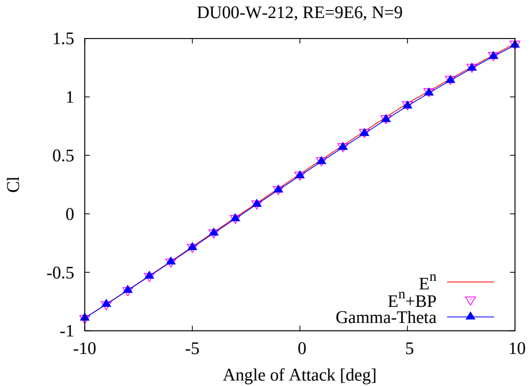
# Test Case, DU00-W-212
## Lift, Natural Transition





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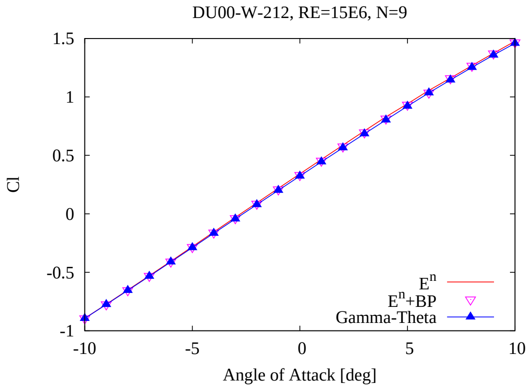
# Test Case, DU00-W-212
## Lift, Natural Transition





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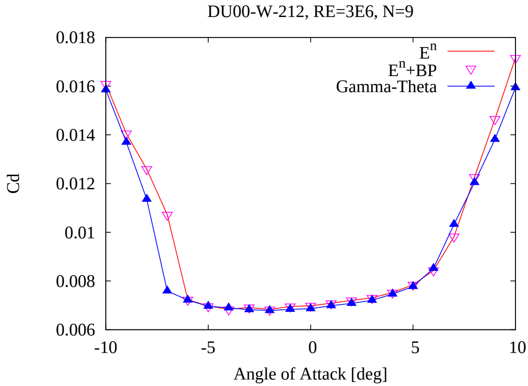
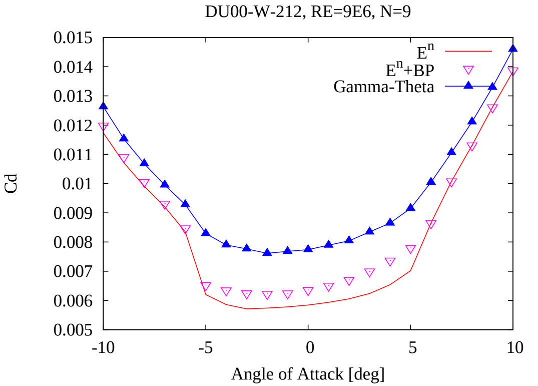
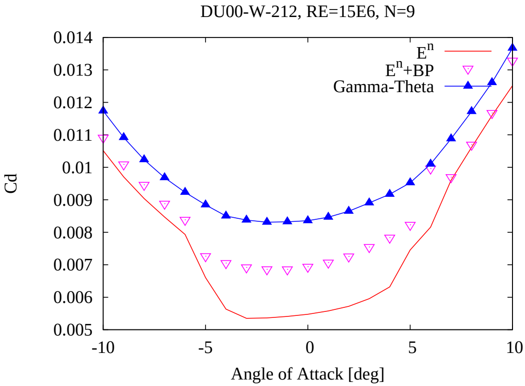
# Test Case, DU00-W-212
## Drag, Natural Transition



# Test Case, DU00-W-212
## Drag, Natural Transition



# Test Case, DU00-W-212
## Drag, Natural Transition





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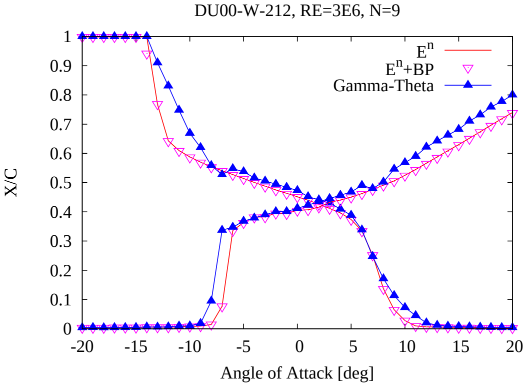
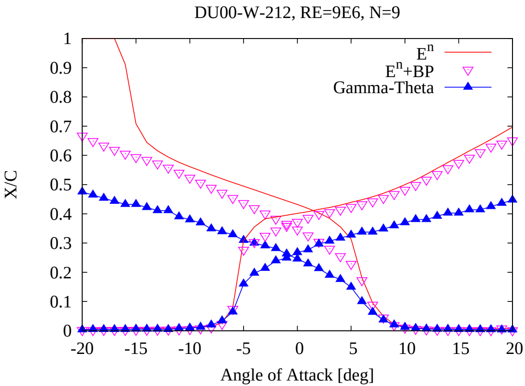
# Test Case, DU00-W-212
## Transition Location, Natural Transition



# Test Case, DU00-W-212
## Transition Location, Natural Transition



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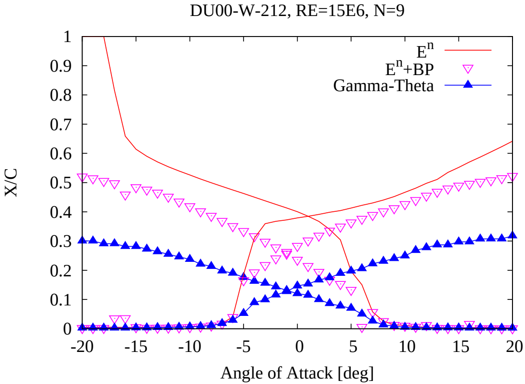
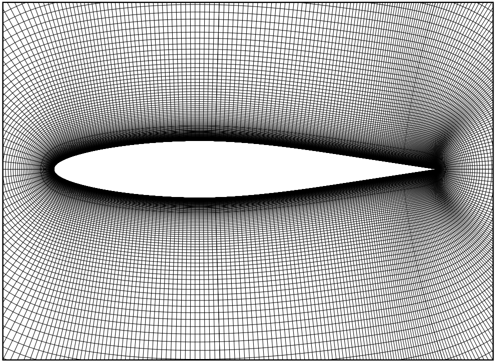
# Test Case, DU00-W-212
## Transition Location, Natural Transition

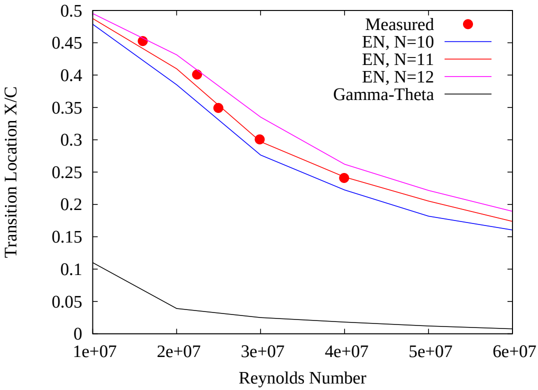


# Test Case, NACA64$_2$A015
## Computational setup

- Airfoil computations for Re=[10:40] million, AOA=0 deg.
- Using two transition models, $E^n$ and $\gamma - Re_\theta$
- Mesh resolution 384 $\times$ 256



## Test Case, NACA64$_2$A015
# Performance at high Re





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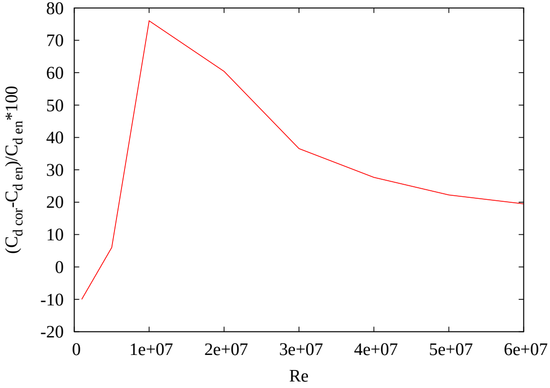
# Test Case, NACA64$_2$A015
## Performance at high Re





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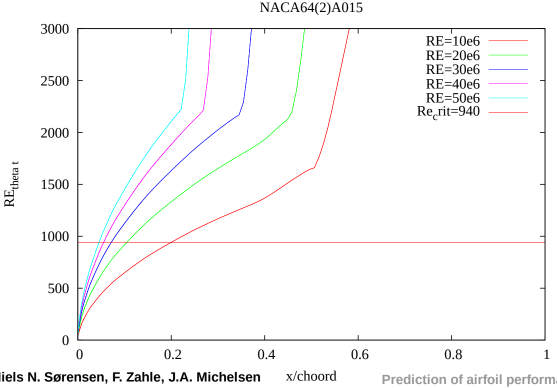
# Explanation

## Behavior of the correlation based model

The following behavior is observed

- The Reynolds number is varied through the viscosity
- The pressure distribution stays nearly constant
- Turbulent quantities are unchanged away from the airfoil
- The critical Reynolds number predicted by the $\gamma - Re_\theta$ model stays constant



# Conclusion and outlook

We need further validation at high Re and relatively low Mach

- Wind turbine rotors will face high Re with increasing size
- Lift is weakly dependent on the transition location in normal operation even at high Re
- The available data show that the $\gamma - Re_\theta$ model over-predict drag at high Re
- Very little data available for comparison
- New data will be provided by the AVATAR project for the DU00-W-212 airfoil
- The National Wind Tunnel could provide data Re $\sim$ 10 Mill for low AOA