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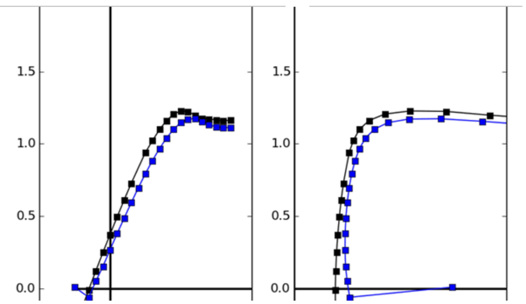


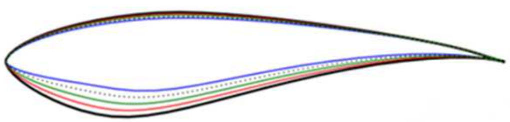

# The National Rotor Testbed: Airfoil Requirements and Selection

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# Airfoil Requirements and Selection

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- Two primary questions:
  - Is the definition of airfoil requirements sufficient and without gaps?
  - Are the chosen airfoils the best candidates to meet these requirements?

# High Level Design Goals

- Design for analysis: NRT rotors must achieve predictable, repeatable performance in relevant operating regimes to support validation efforts

- The selected airfoils must be publicly available and have high-quality, published wind tunnel data

- NRT rotors must replicate rotor loads and wake formation of a utility scale turbine to support turbine-turbine interaction research at SWiFT; i.e. produce wakes of similar geometry, velocity deficit and turbulence intensity.

# Airfoil Selection Drivers

- Predictable rotor performance and stall characteristics
- Specific rotor similarity and performance metrics
- Roughness insensitivity
  - Sensitivity increases as Reynolds number decreases (at least below the design Reynolds number)
- Thickness reqt. for structures (different limits than utility rotor)
  - Also reqt. for instrumentation and access (becomes more important as size decreases)
- Smooth geometric and aerodynamic transitions between airfoils

# Reynolds number effects

- Reynolds numbers will not match between scales – we seek merely to understand and account for the effects
- A reduction in Reynolds number for a given airfoil (generally) causes:
  - Decrease in max $C_l$
  - Increase in profile drag
- Roughness sensitivity depends on the design Reynolds number range
- The scaled rotor design must account for these effects through a combination of planform and airfoil modifications

# Reynolds number effects

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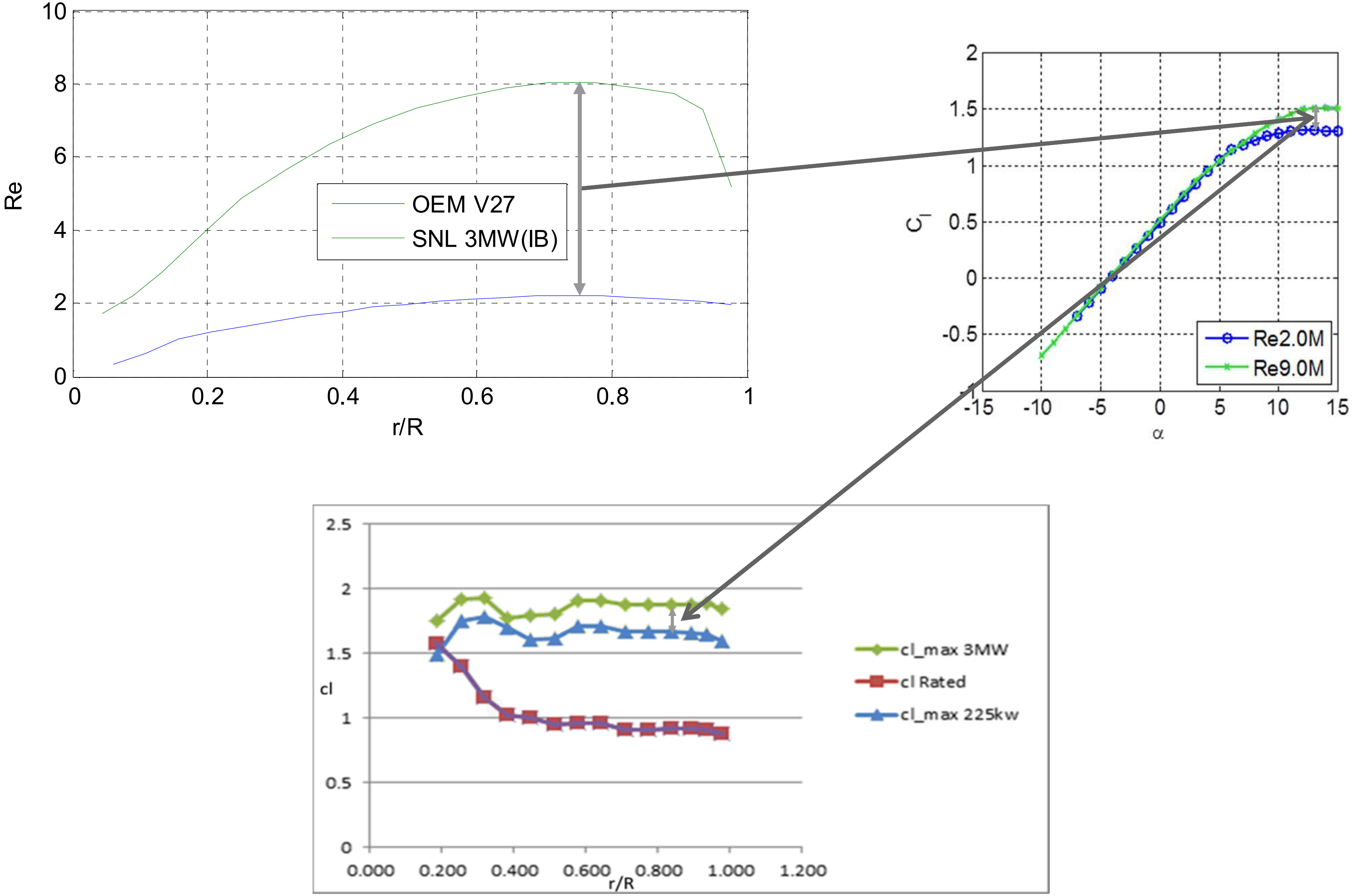
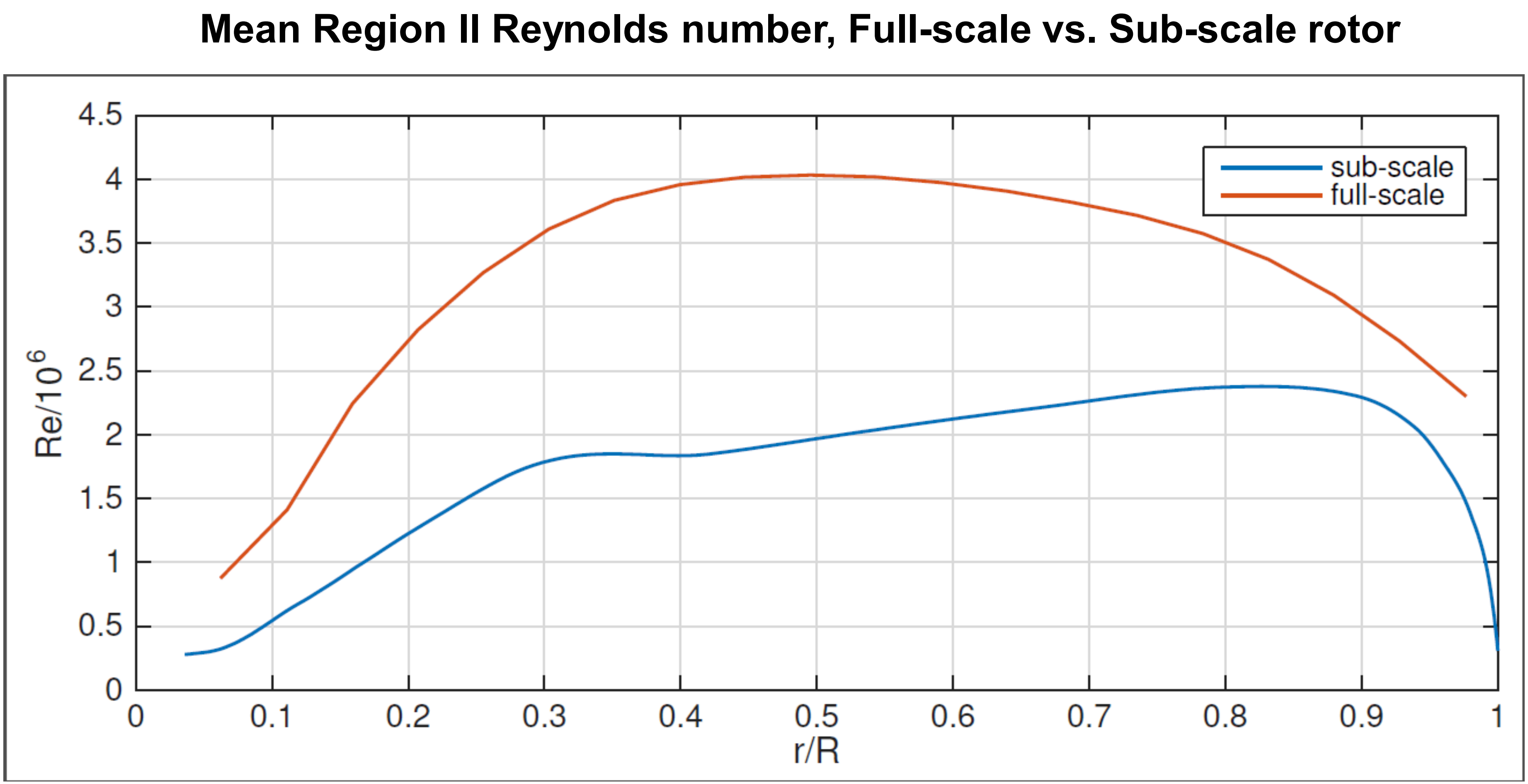


# Reynolds number effects

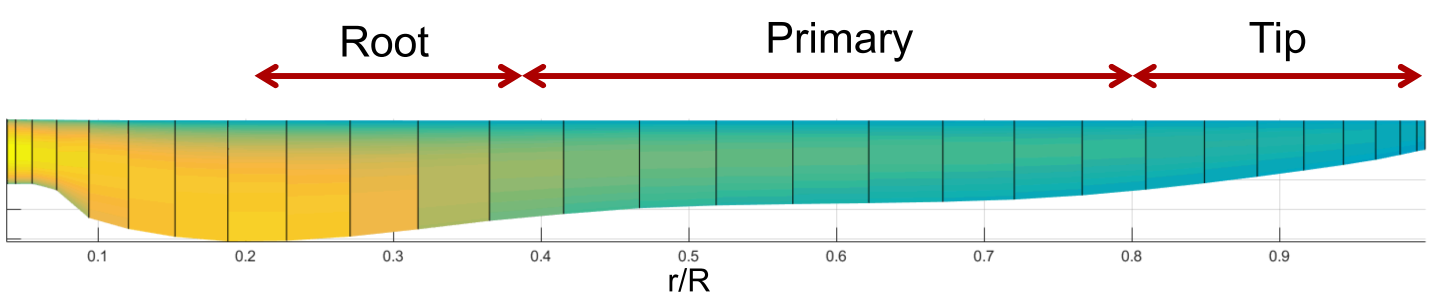


# Airfoil Options

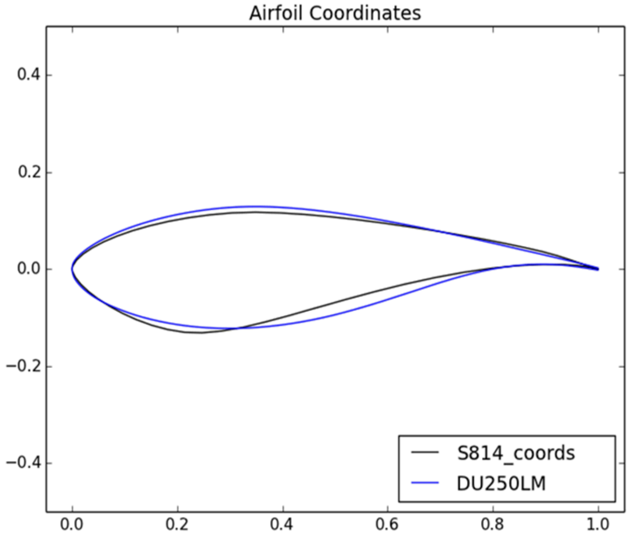
- Focused on two families of airfoils: The 'DU' and the 'S-series'
  - Both were designed in the 1990's for wind turbine applications are were tested in high-quality wind tunnels
  - DU designed for 3 million Reynolds number
  - S-series designed for 1-2 million Reynolds

**Scaled Rotor Reynold's Number Operation in Region-2**

| Blade Region | Reynold's Number | S-series | DU-series |
|---|---|---|---|
| Root | 1,000,000 | S814 | DU-250 |
| Primary | 2,000,000 | S825 | DU-210 |
| Tip | 1,500,000 | S825 | DU-180 |



# Airfoil Options: Root

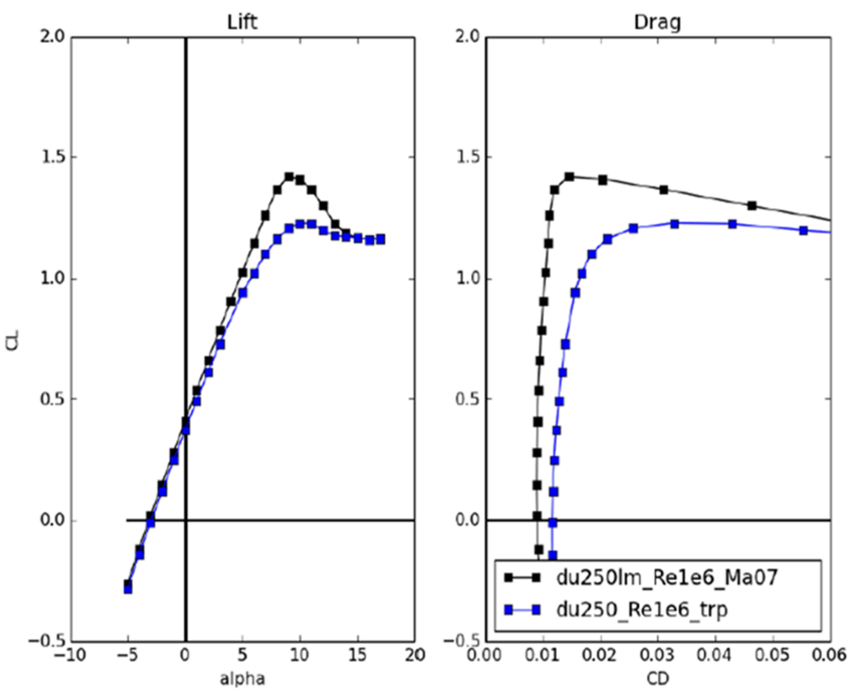



- DU 91-W2-250 (~25% thick)
  - Design ReNum 3e6
  - + Thicker
  - + Relevant to modern wind turbines
  - + Tested in high quality tunnel (Delft)
  - - Only a limited amount of the data has been published
- S814 (~24% thick)
  - Design for 40% span, ReNum 1.5e6
  - + Performance at ReNum 3e6 looks good. This airfoil could be used on modern utility scale turbines. Very insensitive to standard roughness at ReNum 3e6
  - + Tested at Delft and Ohio State. Delft data includes transition, covers 0.7e6 to 3e6 ReNum from ~ zero lift to past stall (AoA = {-5 deg -> 20 deg.})
  - + Wind tunnel data is well published in several reports

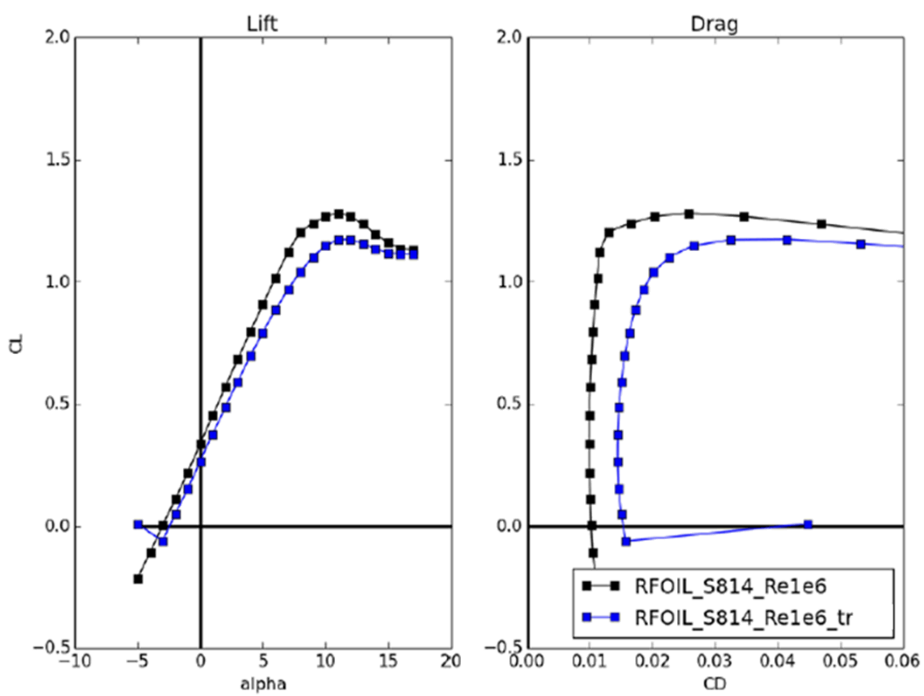
# Airfoil Options: Root

DU 91-W2-250 (~25% thick)

S814 (~24% thick)



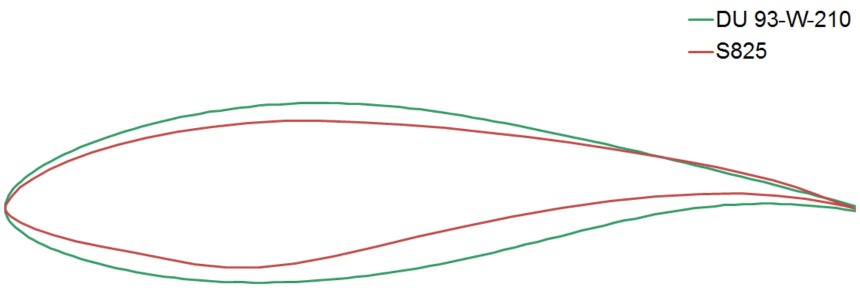

DU Root Airfoil Polar, DU-250, at Re = 1e6.




S-series Root Airfoil Polar, S814, at Re = 1e6.

# Airfoil Options: Primary

- DU 93-W-210 (~21% thick)
  - Design ReNum 3e6
  - + Much thicker
  - + Relevant to modern wind turbines
  - + Tested in high quality tunnel (Delft). Data is archived and some is published.
  - - Only a limited amount of the data has been published (2e6)




- S825 (~17% thick)
  - Design for 75% span of a 20m to 40m variable speed, variable pitch HAWT
    - Design ReNum 2e6
  - + Performance at higher ReNum 3e6 is good. This airfoil could be used on modern utility scale turbines. Very insensitive to standard roughness at ReNum 2-6e6
  - + Tested at NASA Langley LTPT and Ohio State. NASA data includes transition, covers 1e6 to 6e6 ReNum from ~ zero lift to past stall, including hysterisis

# Airfoil Options : Primary

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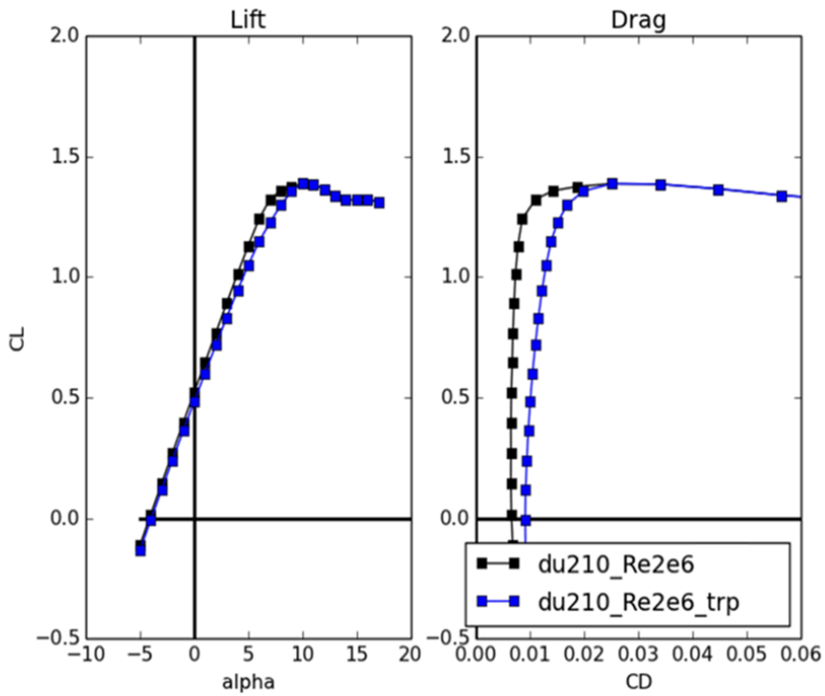
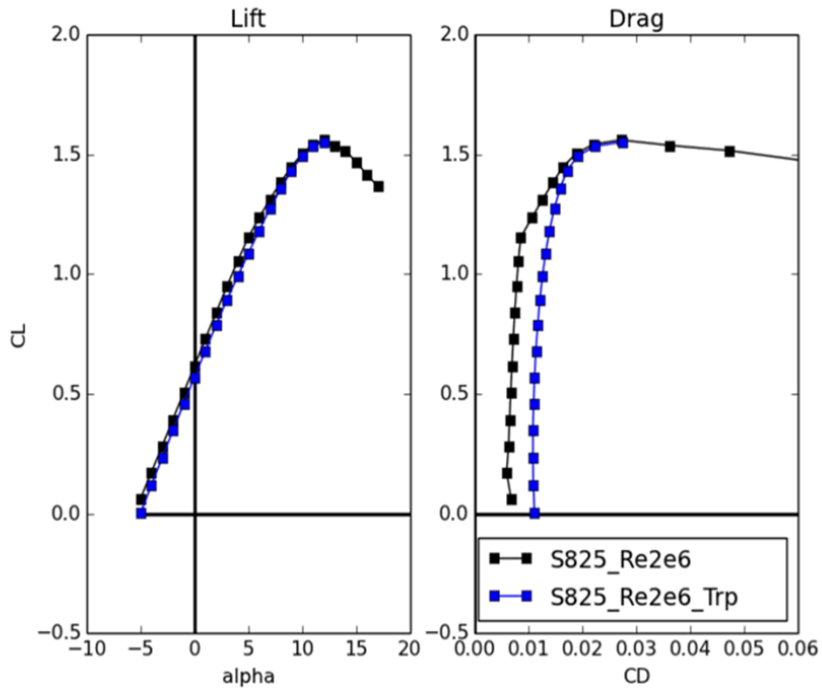
DU 93-W-210 (~21% thick)



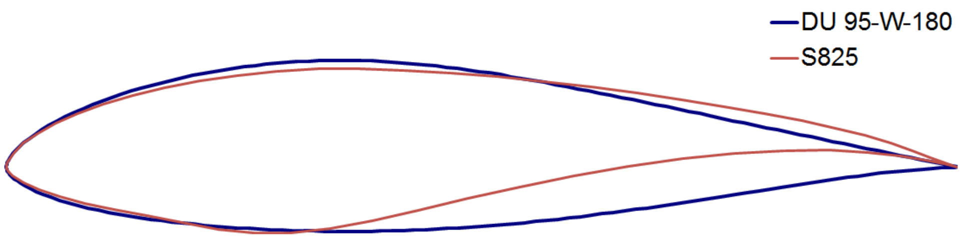

DU Primary Airfoil Polar, DU-210, at Re = 2e6.

S825 (~17% thick)




S-series Primary Airfoil Polar, S825, at Re = 2e6.

# Airfoil Options: Tip

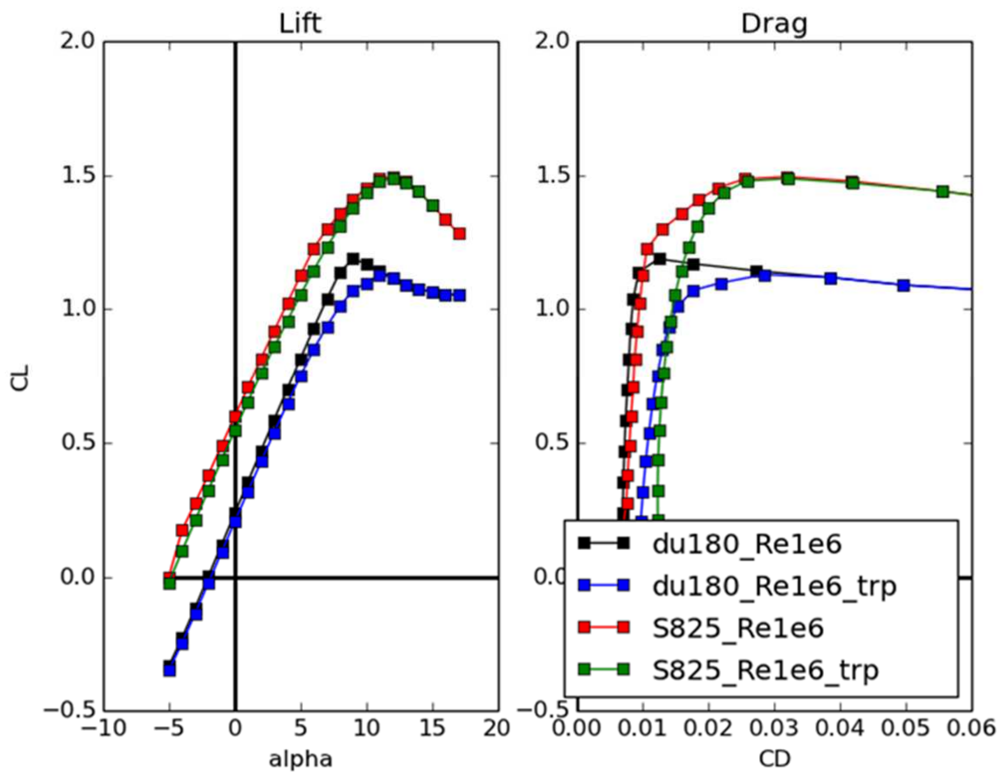



- DU 95-W-180 (~18% thick)
  - Design ReNum 3e6
  - + Relevant to modern wind turbines
  - + Tested in high quality tunnel (Delft).
  - - Only a limited amount of the data has been published (0.7e6, 3e6)

- S825 (~17% thick)
  - Design for 75% span of a 20m to 40m variable speed, variable pitch HAWT
    - Design ReNum 2.0e6
  - + Performance at higher ReNum 3e6 is good. This airfoil could be used on modern utility scale turbines. Very insensitive to standard roughness at ReNum 2-6e6
  - + Tested at NASA Langley LTPT and Ohio State. NASA data includes transition, covers 1e6 to 6e6 ReNum from ~ zero lift to past stall, including hysterisis

# Airfoil Options : Tip

DU 95-W-180 (~18% thick) vs. S825 (~17% thick)




- Results are both from RFOIL, as experimental results have not been published for the DU-95-W-180 at relevant Reynolds numbers to NRT

# Airfoil Options

- Four options were selected for comparison:

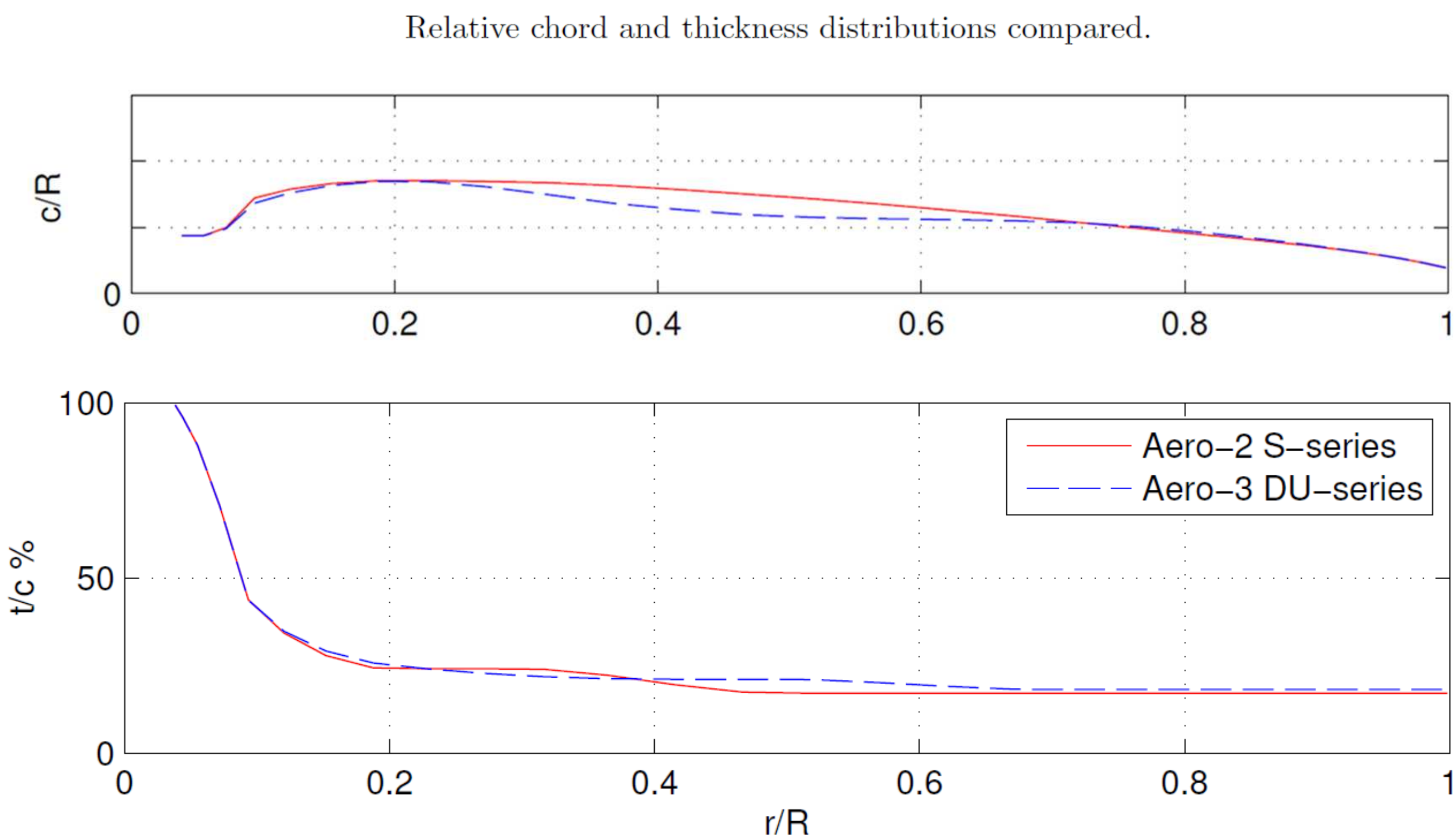
| | | |
|---|---|---|
| **Proposal A** | DU | **DU95-W-180**/ **DU93-W2-210**/ **DU95-W2-250**/ DU97-W-300 |
| **Proposal B** | S814/825 | S815/ **S814**/ **S825**/ S826 |
| **Proposal C** | S814/TR/825 | S815/ **S814**/ New-Airfoil/ **S825**/ S826 |
| **Proposal D** | New Airfoils | All new airfoils, design and testing |

- Two blades were designed to compare the performance effects of the two primary airfoil families

| | Aero-2 (S-series) | Aero-3 (DU) |
|---|---|---|
| Root | S814<br>(24% thick) | DU 91-W2-250<br>(25% thick) |
| Primary | S825<br>(17% thick) | DU 93-W-210<br>(21% thick) |
| Tip | S825<br>(17% thick) | DU 95-W-180<br>(18% thick) |

# Analysis Description

- The relative performance of these two blades was analyzed using WT_Perf and AeroDyn



# Airfoil Requirements and Comparison

- The four proposed airfoil options have been ranked for nine requirements
- The requirements were weighted relative to each other based on priority
- Each airfoil family option was ranked for each requirement on a scale of 1 to 5, and then weighted

# Requirement 1: Thickness Requirements

Airfoils used in the rotor design should be as thick as is reasonable.

- Both conceptual blade designs utilize 25% thick airfoils near the blade root
- Thicker airfoils are available from the DU family of airfoils, but they show increased roughness sensitivity at the operating Reynolds number of the NRT blades
- The current rotor design with a 25% thick root airfoil meets stiffness requirements

# Requirement 2: Schedule

Design and testing of new airfoils or testing of existing airfoils could require significant project time. The use of the proposed airfoil family should not delay the deployment of the NRT blades.

- Designing and testing new airfoils would delay the current schedule
- The use of the S-series or DU airfoil families will not effect the schedule

# Requirement 3:  Experimental Data and Quality

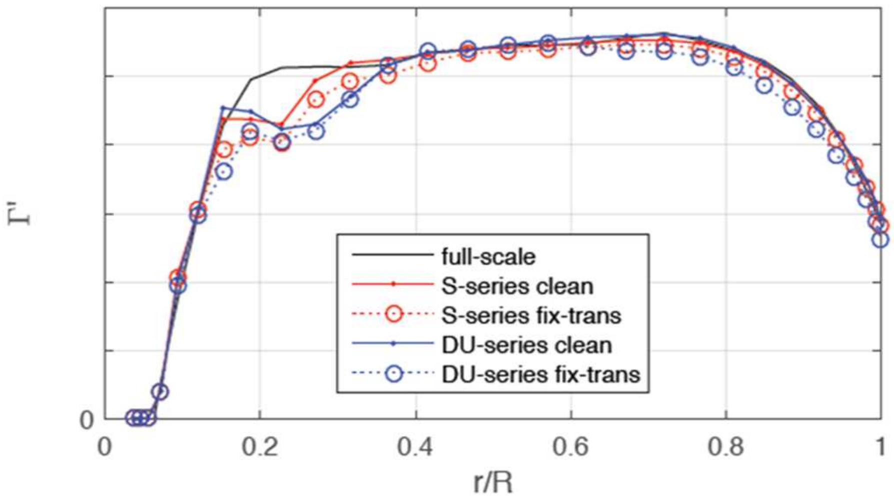
Airfoils shall have thoroughly documented, publicly available airfoil polars taken in a high-quality wind tunnel.

- Both airfoil families have a significant amount of publicly available, high-quality wind tunnel data
- The S-series airfoils have a more publicly available data, in particular additional data on roughness effects

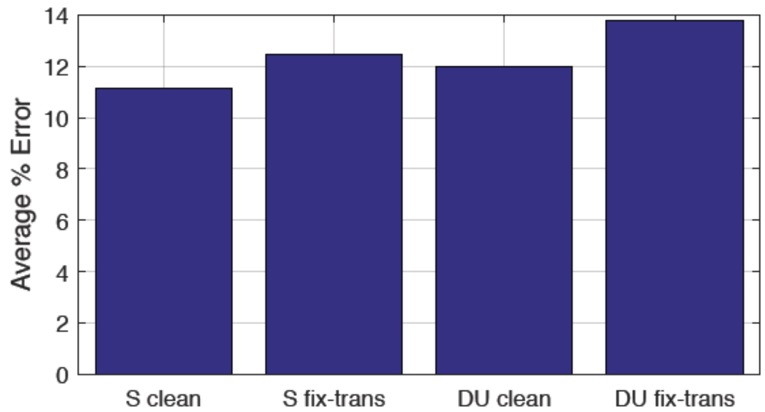
# Requirement 4: Region II Similarity

The airfoil family shall enable replication of the mean and variability in circulation distribution of the full-scale rotor during operation in turbulent inflow.

**Circulation distribution**




**Integrated error in circulation distribution**




- The Aero-2 blade (S-series) has slightly lower error near the blade root and tip under low turbulence conditions

# Requirement 4: Region II Similarity

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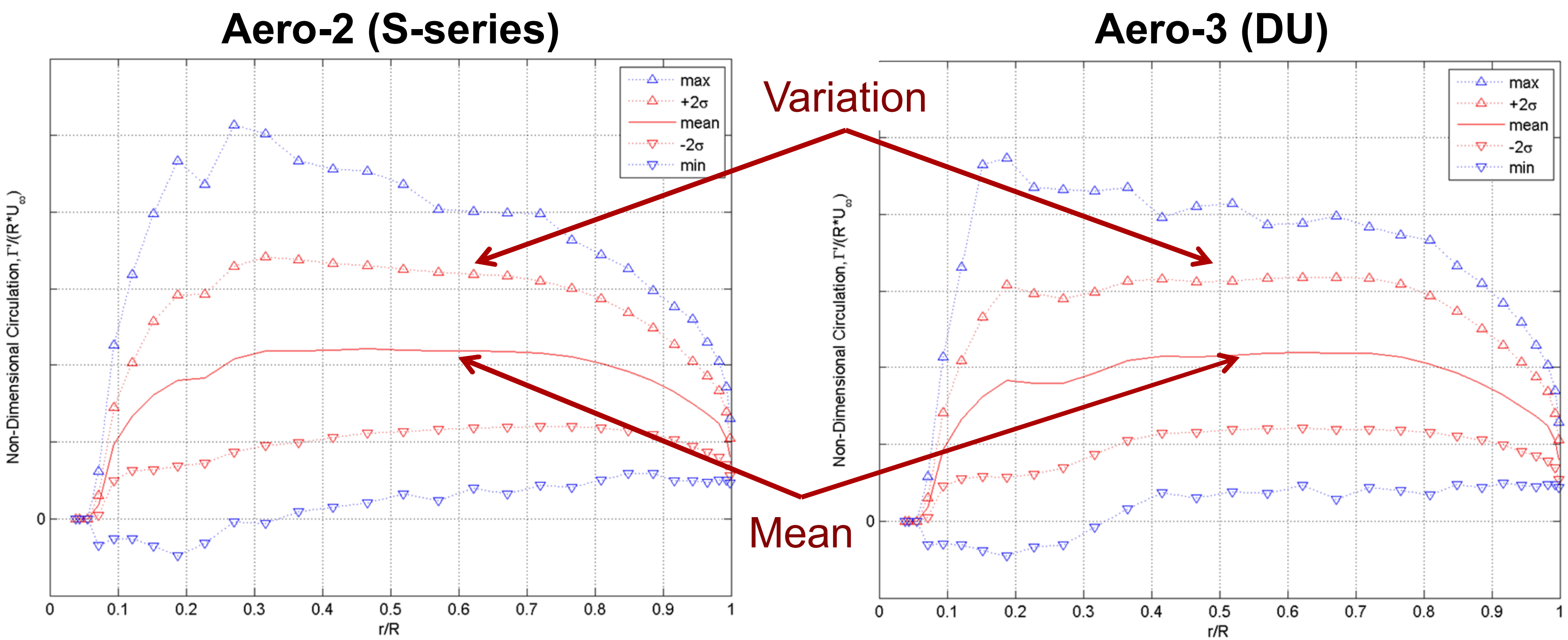
The airfoil family shall enable replication of the mean and <u>variability</u> in circulation distribution of the full-scale rotor during operation in turbulent inflow.



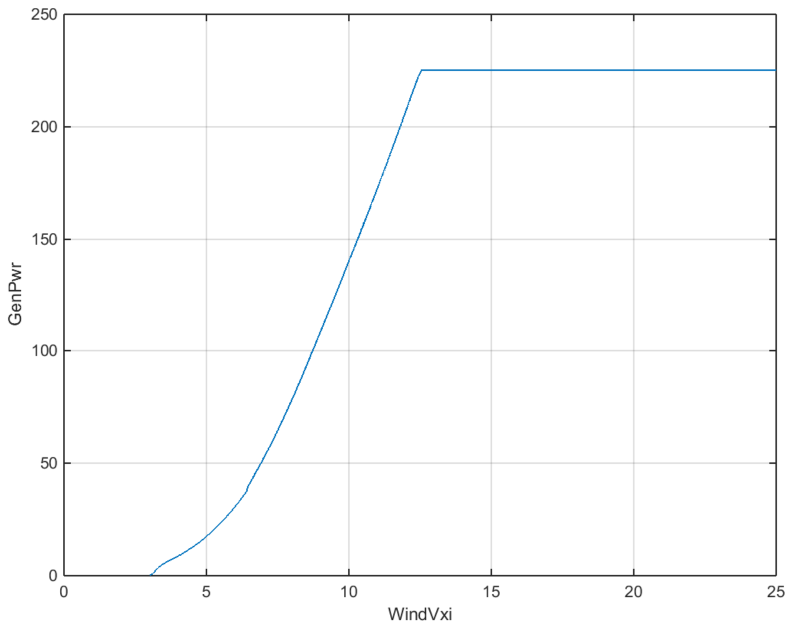

**Circulation Profile and Variation for top of Region II, 6 m/s, IEC Class C Turbulence**

- Change in circulation distribution due to turbulent inflow
- Each blade was modeled in FAST under IEC turbulence cases
- The variability of the two blades was similar

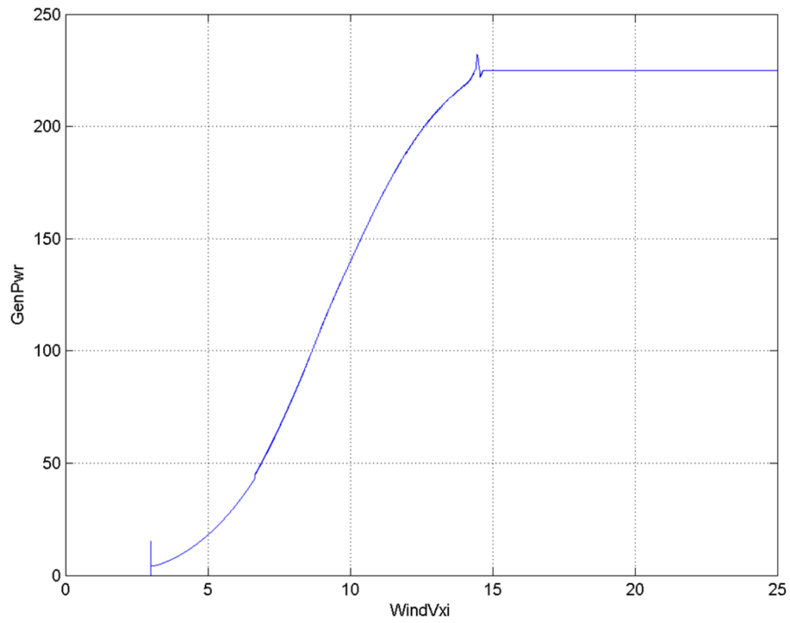
# Requirement 5: Region II.5 Performance

Airfoils shall enable a rotor in which the operating angle of attack is sufficiently below stall over most of Region II.5---therefore enabling the rotor is able to reach rated power after reaching maximum allowable rotor speed.

**Aero-2 (S-series)**




**Aero-3 (DU)**




**Blade Design Steady Power Curve (Power vs. Wind Speed)**

- Aero-3 reaches rated power at a higher wind speed than Aero-2

# Requirement 6: Roughness Sensitivity

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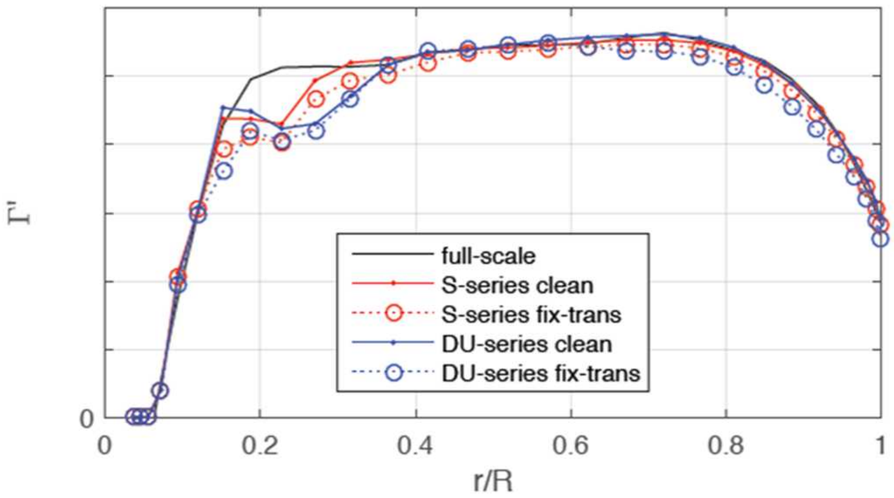
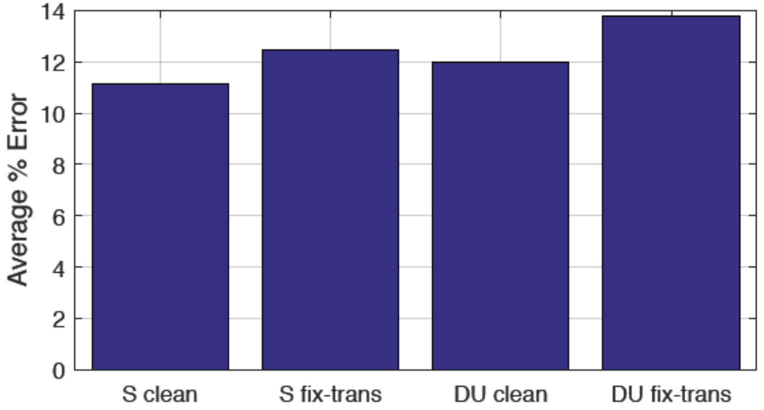
Anticipated changes in surface roughness shall have minimal effect on the intended blade circulation distribution of the rotor.

**Circulation distribution**



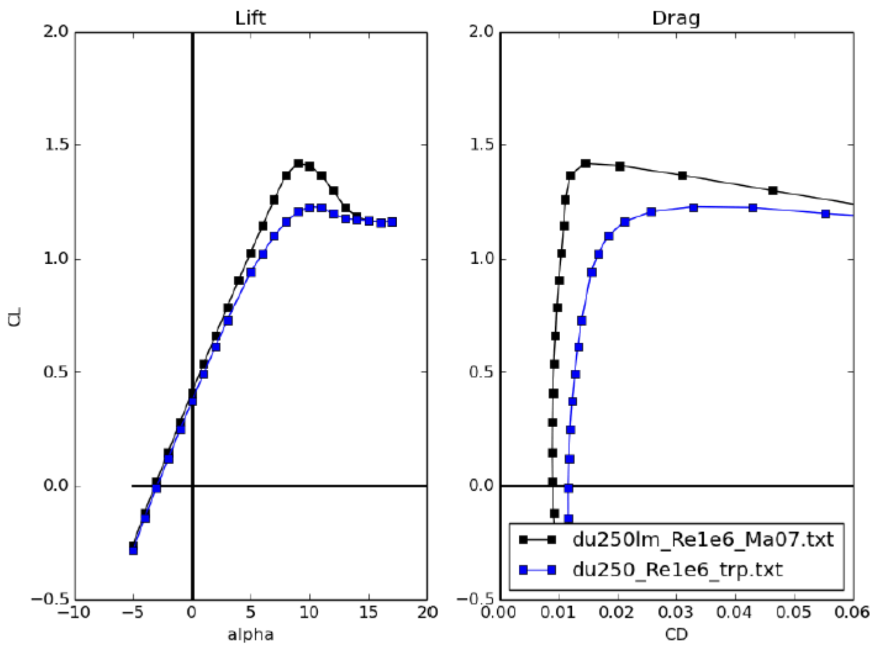

**Integrated error in circulation distribution**



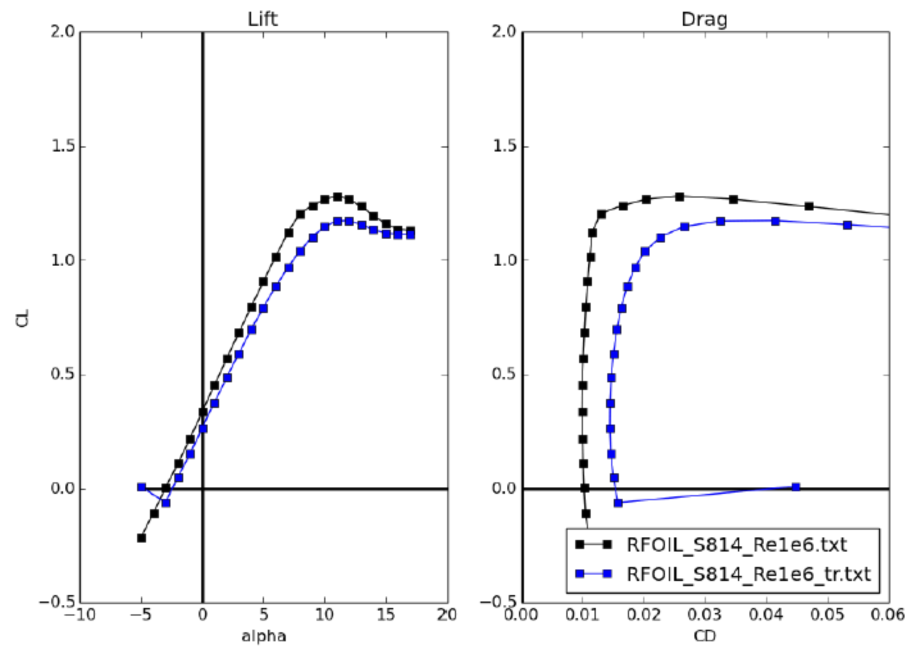

| Airfoil | $C_P$ | $\Delta C_P\%$ | $C_T$ | $\Delta C_T\%$ | $C_Q$ | $\Delta C_Q\%$ |
|---|---|---|---|---|---|---|
| S-series clean (Aero-2) | .4775 | | 0.8681 | | 0.0531 | |
| S-series fixed transition | .4709 | -1.3 | 0.8501 | -2.0 | 0.0523 | -1.5 |
| DU-series clean (Aero-3) | .4851 | | 0.8679 | | 0.0539 | |
| DU-series fixed transition | .4599 | -5.2 | 0.8338 | -3.9 | 0.0511 | -5.2 |

# Requirement 7:  Stall Characteristics

Airfoils shall have docile stall characteristics to promote predictable gust response and to minimize the amplitude of unrepresentative blade elastic bending oscillations.



DU Root Airfoil Polar, DU-250, at Re = 1e6.



S-series Root Airfoil Polar, S814, at Re = 1e6.

- Stall characteristics are similar in tripped condition
- Some of the DU airfoils have sharper stall characteristics in clean condition at NRT Reynolds numbers

# Requirement 8: Field Experience

Airfoils shall have extensive experience in the field at Reynolds numbers which are relevant to the design of this rotor.

- The DU airfoil family has been used on production wind turbine blades
- S-series airfoils have been used in experimental and production blades, but not the airfoils that would be used on the NRT
- Neither airfoil families have been used on a fielded blade at the NRT Reynolds number range

# Requirement 9:  Root airfoil transition region

Airfoils shall have available polar data for thick airfoils which are anticipated in the root-to-maximum-chord transition region of the blade.

- The DU airfoil family includes thicker airfoil sections that can be used in the root-to-maximum-chord transition region

- The S-series airfoil family has a maximum 26% thick airfoil, and will rely primarily on interpolated airfoil section in the root-to-maximum-chord transition region

# Requirements Relative Weighting

| Thickness Requirements | Schedule | Experimental Data and Quality | Region II Similarity | Region II.5 Performance | Roughness Sensitivity | Stall Characteristics | Field Experience | Root airfoil transition region |
|---|---|---|---|---|---|---|---|---|
| 0.5 | 2.0 | 1.4 | 1.0 | 0.4 | 0.7 | 0.5 | 0.2 | 0.7 |

- Schedule and 'Experimental Data and Quality' were given the highest weights
- 'Stall Characteristics' and 'Roughness Sensitivity' were given relatively low importance, since their effects are captured in other categories
- Region II.5 Performance was not deemed critically important, only desirable
- Past field experience was not viewed as very important

# Airfoil Options

| Category | Thickness Requirements | Schedule | Experimental Data and Quality | Region II Similarity | Region II.5 Performance | Roughness Sensitivity | Stall Characteristics | Field Experience | Root airfoil transition region | Total |
|---|---|---|---|---|---|---|---|---|---|---|
| **Relative Weight** | 0.5 | 2.0 | 1.4 | 1.0 | 0.4 | 0.7 | 0.5 | 0.2 | 0.7 | 7.4 |
| **DU** | | | | | | | | | | |
| **S814/815/825** | | | | | | | | | | |
| **S814/815/TR/825** | | | | | | | | | | |
| **New Airfoils** | | | | | | | | | | |

| | | |
|---|---|---|
| **Proposal A** | DU | **DU95-W-180**/ **DU93-W2-210**/ **DU95-W2-250**/ DU97-W-300 |
| **Proposal B** | S814/825 | S815/ **S814**/ **S825**/ S826 |
| **Proposal C** | S814/TR/825 | S815/ **S814**/ New-Airfoil/ **S825**/ S826 |
| **Proposal D** | New Airfoils | All New Airfoils |

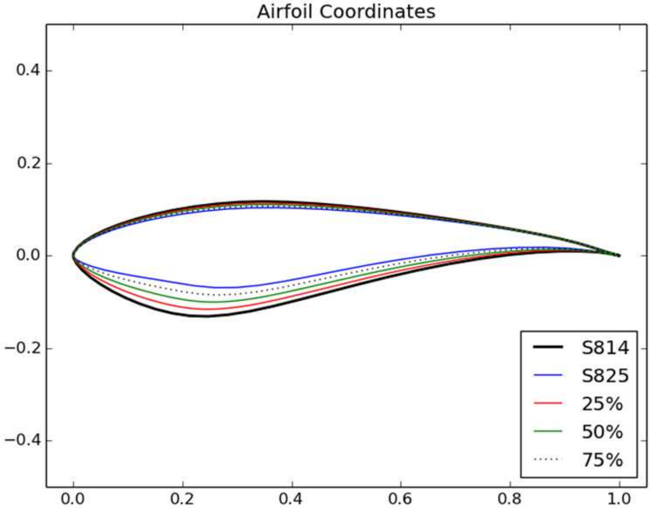
# Weighted Scores

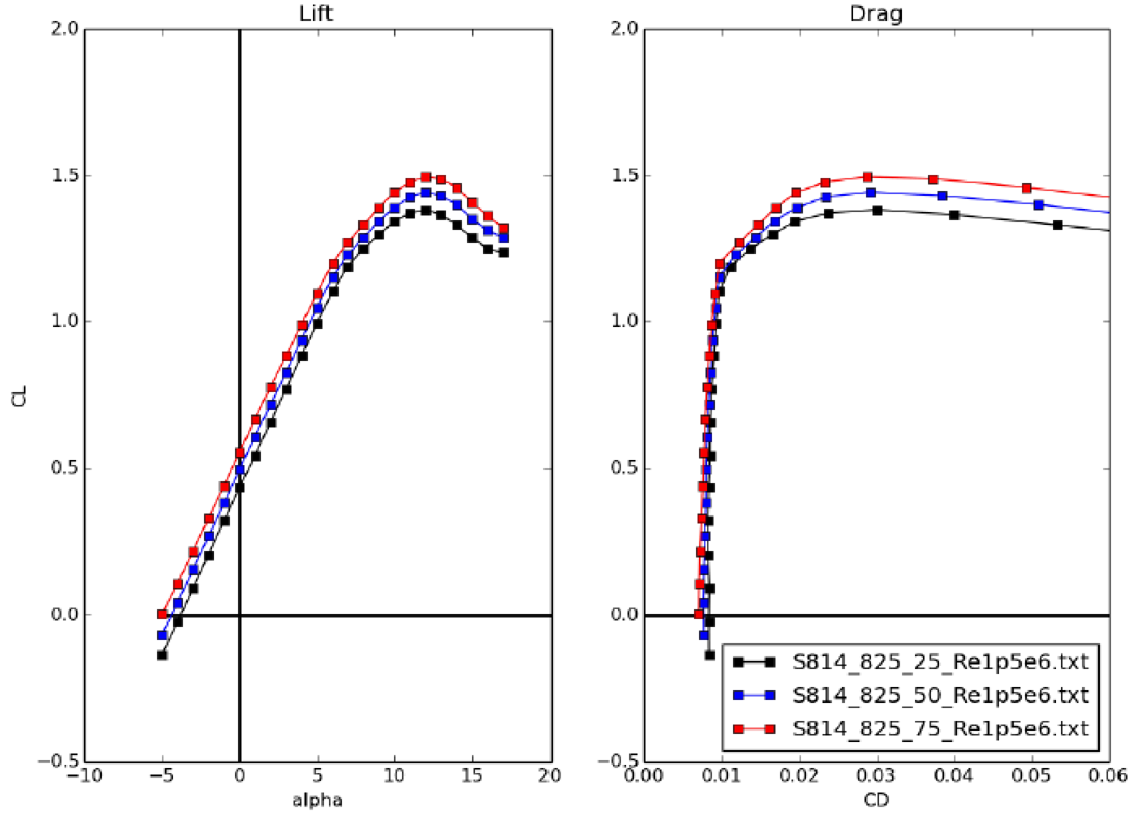
| Category | Thickness Requirements | Schedule | Experimental Data and Quality | Region II Similarity | Region II.5 Performance | Roughness Sensitivity | Stall Characteristics | Field Experience | Root airfoil transition region | Total |
|---|---|---|---|---|---|---|---|---|---|---|
| **Relative Weight** | 0.5 | 2.0 | 1.4 | 1.0 | 0.4 | 0.7 | 0.5 | 0.2 | 0.7 | |
| **DU** | 2.0 | 8.0 | 5.0 | 3.0 | 1.2 | 1.4 | 1.0 | 0.4 | 2.8 | 24.8 |
| **S814/815/825** | 1.3 | 8.0 | 5.5 | 3.0 | 1.6 | 2.8 | 1.5 | 0.2 | 1.4 | 25.2 |
| **S814/815/TR/825** | 1.3 | 6.0 | 4.2 | 3.0 | 1.6 | 2.8 | 1.5 | 0.2 | 2.1 | 22.7 |
| **New Airfoils** | 2.0 | 2.0 | 5.6 | 3.0 | 1.6 | 2.8 | 2.0 | 0.2 | 2.8 | 22.0 |

- **Without ‘Schedule’ requirement, New Airfoils scored highest**
- **The S-series with a new transition airfoil did not score well due to ‘Schedule’ and ‘Experimental Data and Quality’**
- **The S-series airfoil family scored highest due to:**
  - More high-quality, publicly available wind tunnel data
  - Lower roughness sensitivity at NRT Reynolds number range
  - Better Region II.5 performance than a blade designed using DU

# Mid-span Airfoil Transition Verification

- **Requirement:** The outer rotor shall have no jump in spanwise pressure gradient




  - The mid-span transition region shows smooth transition between airfoil characteristics (RFOIL analysis)
  - Blade geometry resolved CFD is being performed as well

# Summary

- Two airfoil families were selected to focus on:
  - DU and S-series
- Four options were analyzed:

| | |
|---|---|
| **Proposal A** | DU |
| **Proposal B** | S814/825 |
| **Proposal C** | S814/TR/825 |
| **Proposal D** | New Airfoils |

- This four options were scored in nine categories that represent the airfoil requirements of the NRT
- Proposal B scored the highest
  - All scores were close
  - Schedule eliminated Proposals C & D (New Airfoils)
  - Data availability and Design Reynolds number were the primary advantages of Proposal B (S-series)

# Acknowledgements

- Dan Somers (Airfoils Inc.)
- Nando Timmer (TU Delft)

- This research was funded by the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy (EERE) program.

*Thank you*

# Backup Slides

# Un-Weighted Scores

| Category | Thickness Requirements | Schedule | Experimental Data and Quality | Region II Similarity | Region II.5 Performance | Roughness Sensitivity | Stall Characteristics | Field Experience | Root airfoil transition region |
|---|---|---|---|---|---|---|---|---|---|
| **Relative Weight** | 0.50 | 2.00 | 1.40 | 1.00 | 0.40 | 0.70 | 0.50 | 0.20 | 0.70 |
| | | | | | | | | | |
| **DU** | 4 | 4 | 3.6 | 3 | 3 | 2 | 2 | 2 | 4 |
| **S814/815/825** | 2.5 | 4 | 3.9 | 3 | 4 | 4 | 3 | 1 | 2 |
| **S814/815/TR/825** | 2.5 | 3 | 3 | 3 | 4 | 4 | 3 | 1 | 3 |
| **New Airfoils** | 4 | 1 | 4 | 3 | 4 | 4 | 4 | 1 | 4 |

# Roughness Insensitivity

- Roughness insensitivity
  - Modern (relatively) airfoils are designed to be insensitive at design Reynolds number
    - We are operating below that design point for airfoils meant for utility scale
  - Sensitivity increases as Reynolds number decreases (at least below the design Reynolds number)
  - Sensitivity increases with thicker airfoils
- Can give up peak performance to make performance less sensitive to roughness
  - Lower design cl: means higher solidity and stronger gust response

# Roughness Insensitivity



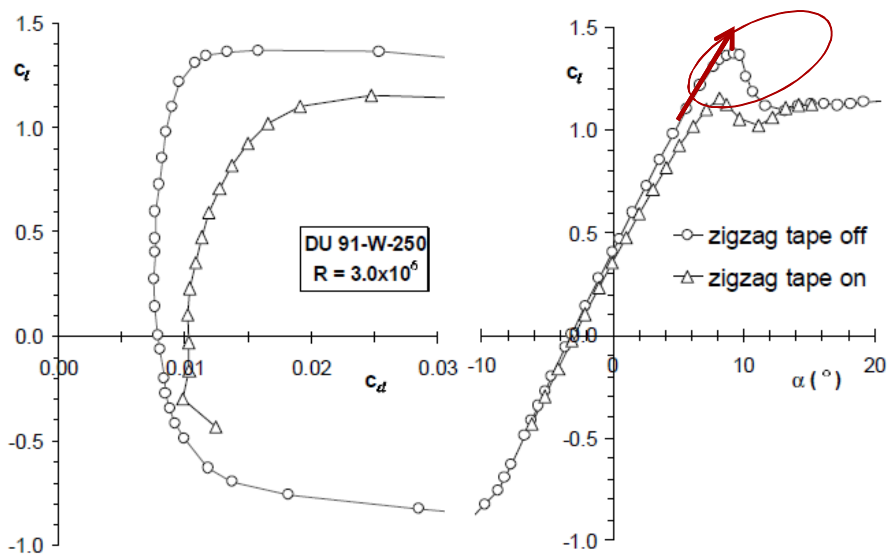



**Figure 5: Measured airfoil performance of DU 91-W2-250 at R=3x10[6].**

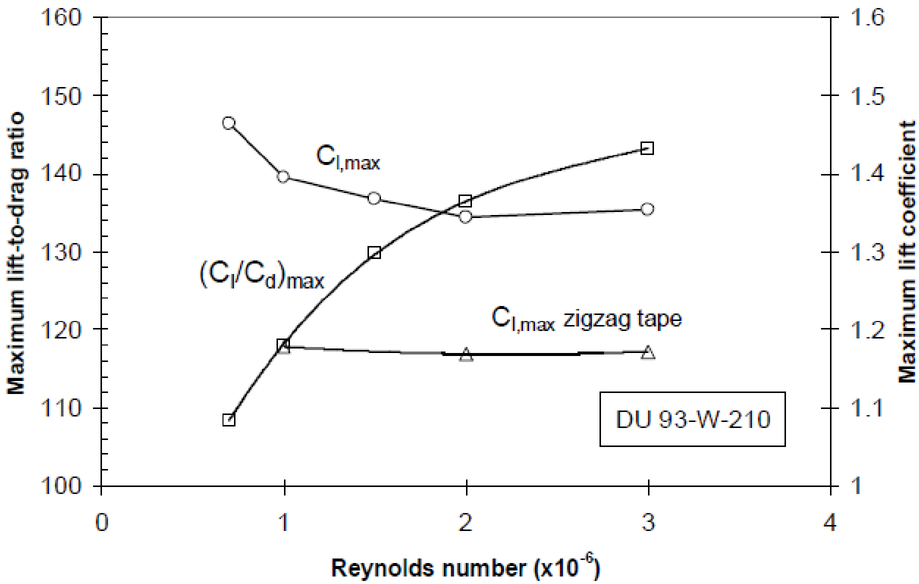



**Figure 7: The effect of Reynolds number on the maximum lift-drag ratio and maximum lift coefficient of airfoil DU 93-W-210**

# Profil Analysis: Effect of Roughness

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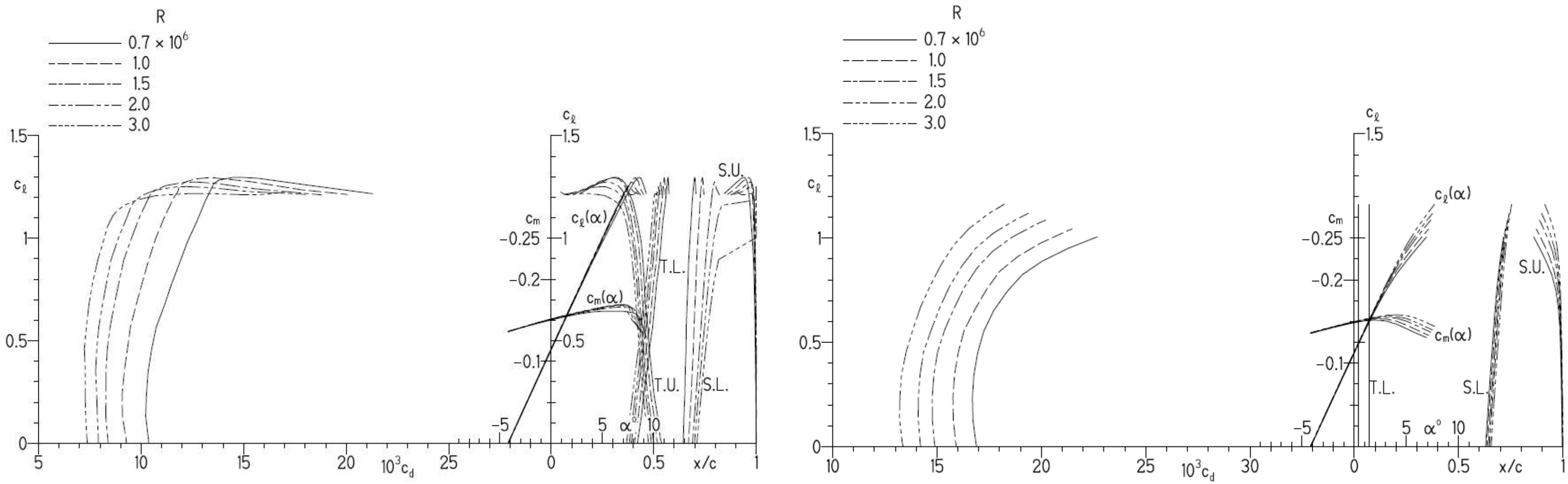



(a) Transition free.

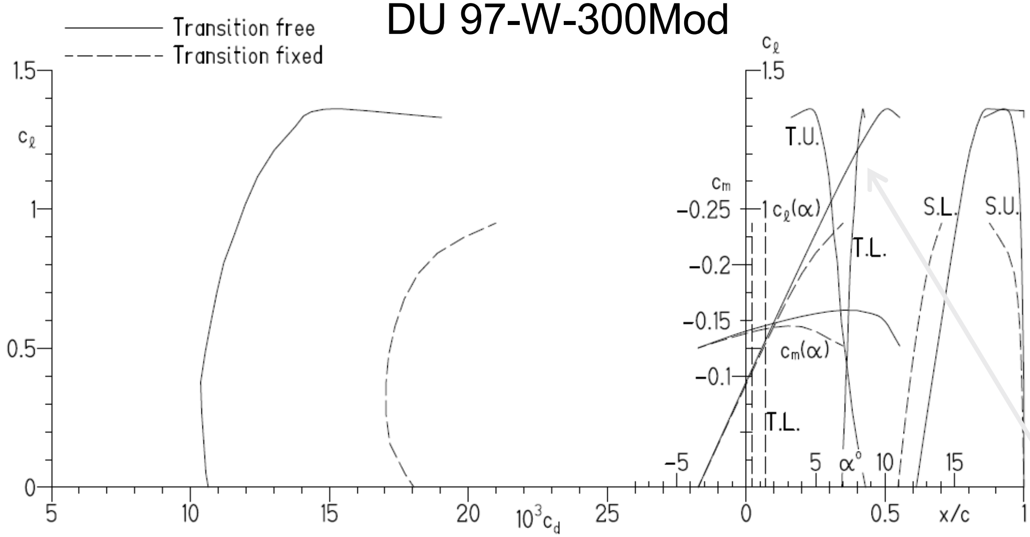
(b) Transition fixed.

Effects of Reynolds number on theoretical section characteristics of DU 91-W2-250 airfoil.

- Under predicted maximum lift, so results are conservative.

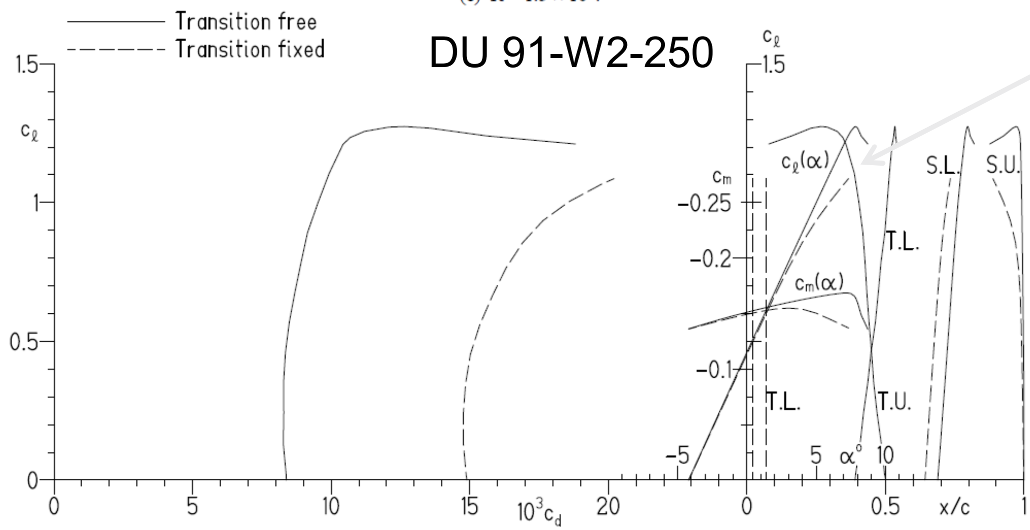
# Profil Analysis: Effect of Roughness

DU 97-W-300Mod




(c) $R = 1.5 \times 10^6$.

DU 91-W2-250




(c) $R = 1.5 \times 10^6$.

The 30% thick airfoil has a larger decrease in maximum lift due to roughness than the 25% thick airfoil.

DU91-W2-250lm: Wind Tunnel,RFOIL and Overflow Results