Part III: Airfoil Data

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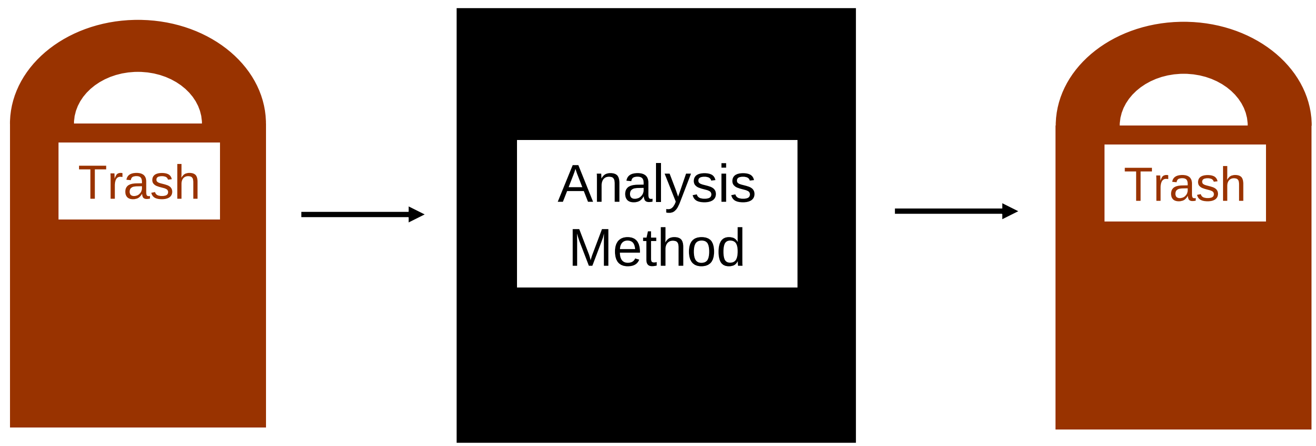
Steady-State Aerodynamics Codes for HAWTs
Selig, Tangler, and Giguère

Outline

- Importance of Airfoil Data
- PROPID Airfoil Data Files
- Interpolation Methods Used by PROPID
- Interpolated Airfoils
- Sources of Airfoil Data
  - Wind tunnel testing
  - Computational methods
- Experimental vs Computational Data

Importance of Airfoil Data in Rotor Design

- Independent of the analysis method...



- Inspect airfoil data before proceeding with design
- Have data over a range of Reynolds number
  - Designing blades with data for only one Reynolds number can mislead the designer

PROPID Airfoil Data Files

- Format
  - Different airfoil mode types, but focus on mode 4
  - Data tabulated for each Reynolds number
  - Separate columns for angle of attack, c_l, c_d, c_m (if available)
  - Data must be provided up to an angle of attack of 27.5 deg.
  - If data not available up to 27.5 deg., need to add data points

- Sample File for the S813 (Airfoil Mode 4)

Number of Reynolds numbers for which data are tabulated

```
emacs@amber.aae.uiuc.edu
Buffers  Files  Tools  Edit  Search  Help
S813  (Eppler data with modifications near stall)
SMOOTH
5
1000000
20
   -3   -0.012    0.0063
   -2    0.098    0.0061
   -1    0.208    0.0061
    0    0.315    0.0062
    1    0.421    0.0063
    2    0.527    0.0064
    3    0.631    0.0066
    4    0.735    0.0069
    5    0.837    0.0071
    6    0.937    0.0075
    7    0.977    0.0162
-----Emacs: s813.pd         7:05pm 0.02 Mail    (Text Fill)--L15--C0--Top--
Find file: ~/propid5080/runs/990802-shortcourse/
```

Comments

First Reynolds number

Angle of attack c_l c_d

Number of data points to follow for first Reynolds number

```
emacs@amber.aae.uiuc.edu
Buffers Files Tools Edit Search Help
   6    0.937    0.0075
   7    0.977    0.0162
   8    1.077    0.0165
   9    1.100    0.0210
  10    1.100    0.0255
  11    1.100    0.0300
  13    1.100    0.0520
  16    1.100    0.1000
  20    1.100    0.1750
  25    1.100    0.2750
  27.5 1.100    0.3630
1500000
20
  -3   -0.012    0.0059
  -2    0.098    0.0057
  -1    0.208    0.0056
-----Emacs: s813.pd        7:05pm 0.02 Mail    (Text Fill)--L15--C0--12%--
Find file: ~/propid5080/runs/990802-shortcourse/
```

Eppler data up to here

Added data points

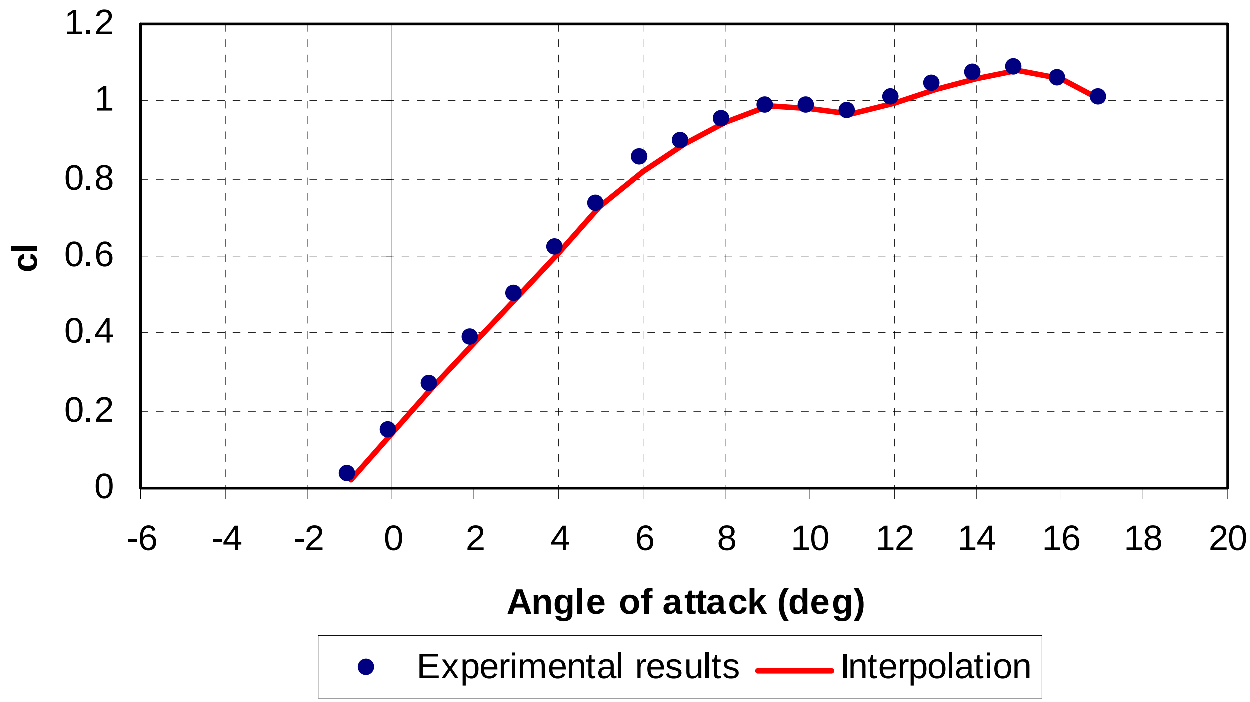
Next Reynolds number

Number of data points to follow for next Reynolds number

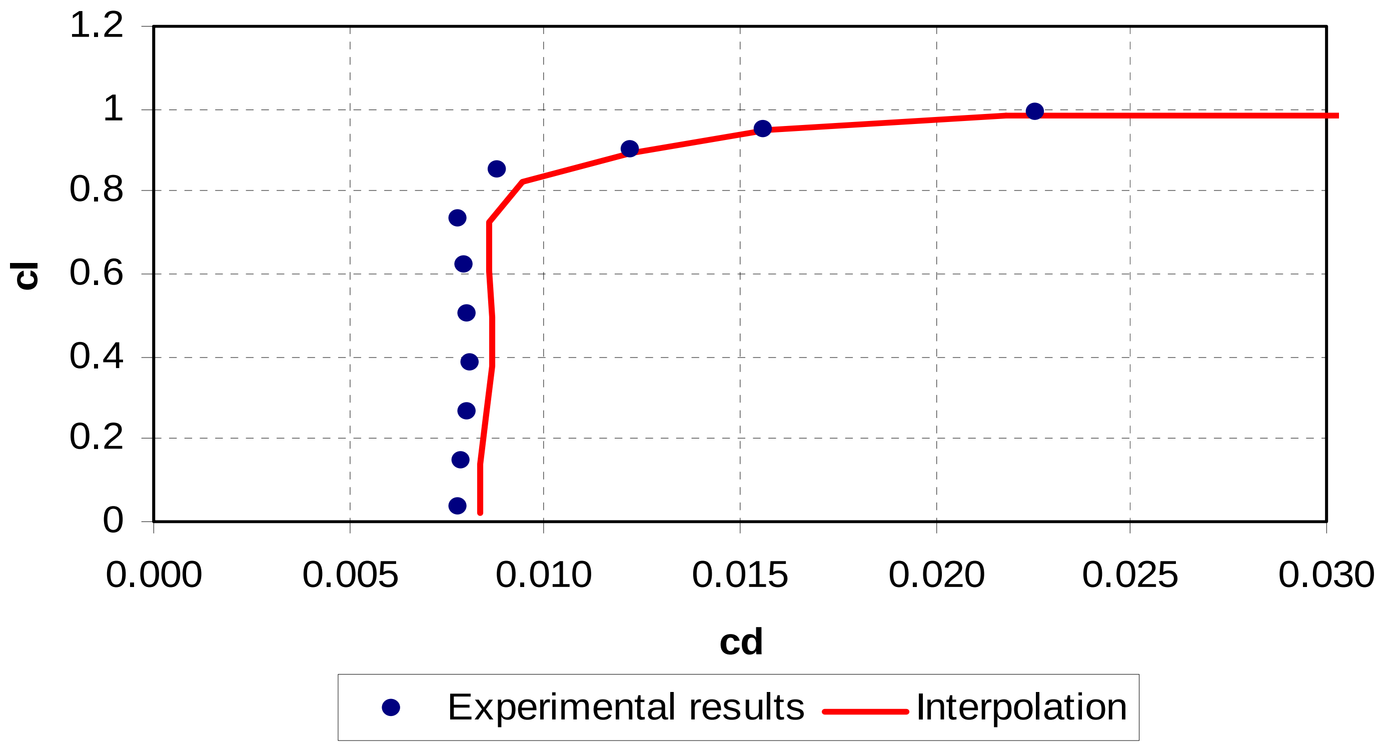
Interpolation Methods Used by PROPID

- Lift
  - Linear interpolation with angle of attack and Reynolds number
- Drag
  - Linear interpolation with angle of attack and logarithmic interpolation with Reynolds number
- No extrapolation of the data

- Interpolation Examples
  - S809 at a Reynolds number of 1,500,000 using data at 1,000,000 and 2,000,000
    - Lift curve



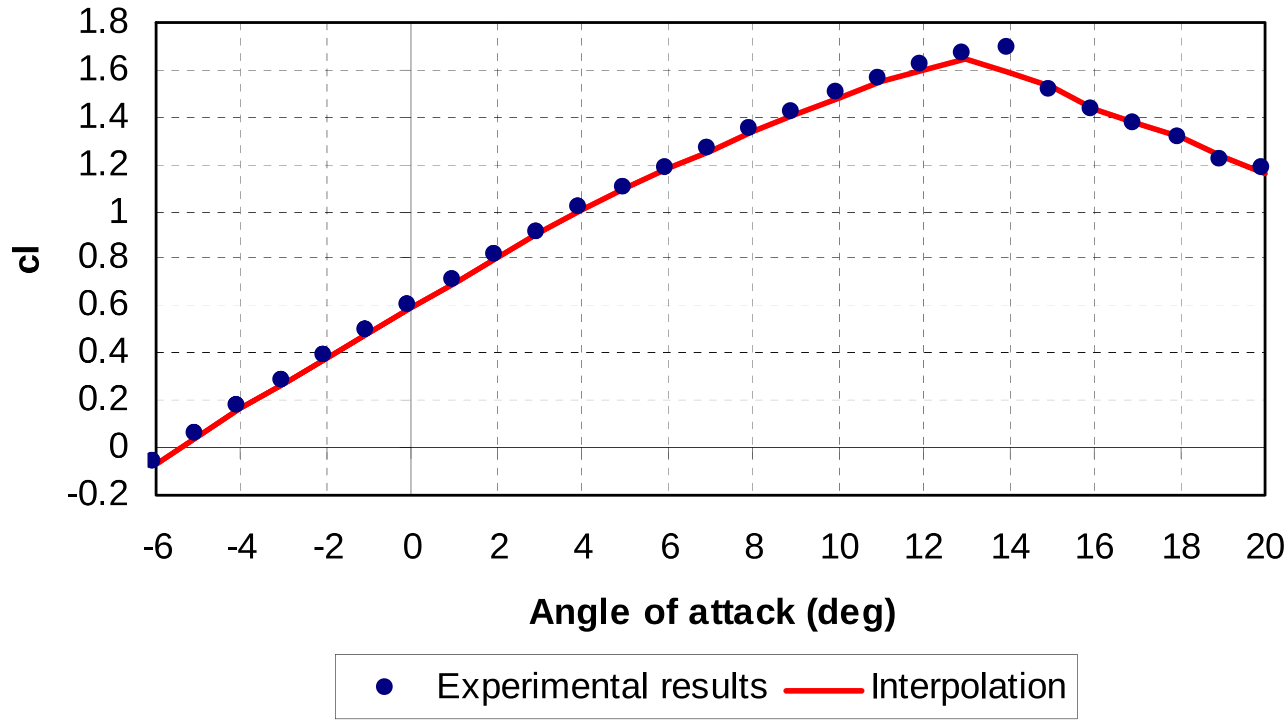
• Drag polar



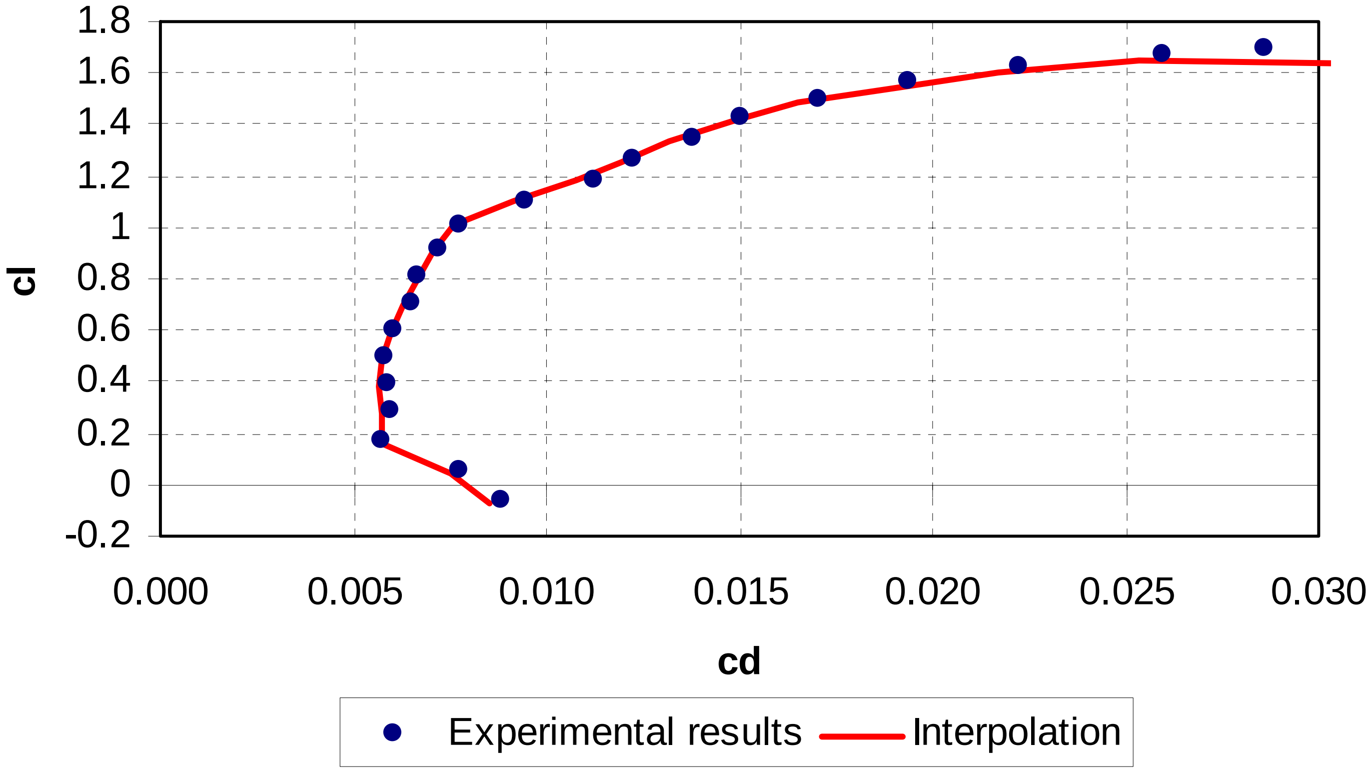
1.2
1
0.8
0.6
0.4
0.2
0
cl
0.000
0.005
0.010
0.015
0.020
0.025
0.030
cd
Experimental results
Interpolation

– S825 at a Reynolds number of 4,000,000 using data at 3,000,000 and 6,000,000

- Lift curve

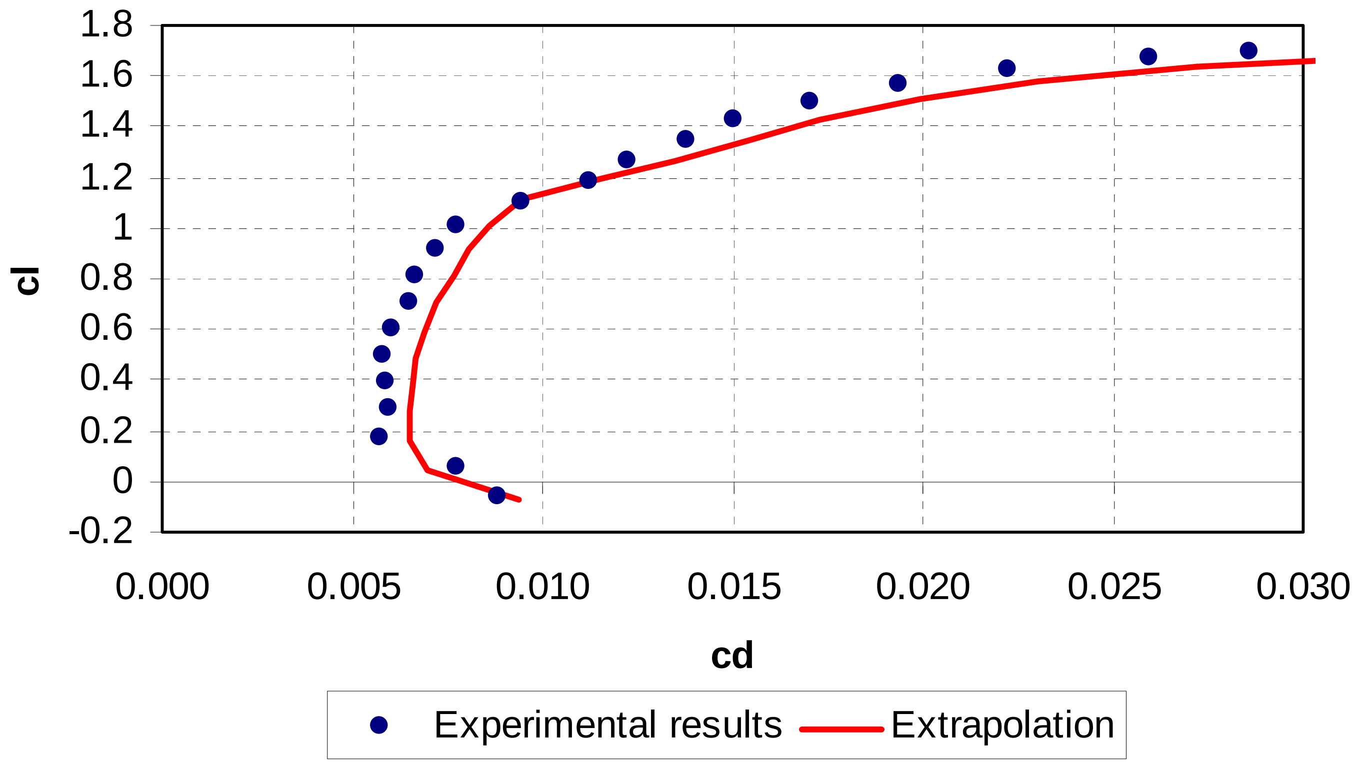


- Drag polar



1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
cl
0.000
0.005
0.010
0.015
0.020
0.025
0.030
cd
Experimental results
Interpolation

- Why Not Extrapolate the Data?
  - Extrapolation not as accurate as interpolation
    - S825 at a Reynolds number of 4,000,000 using data at 2,000,000 and 3,000,000



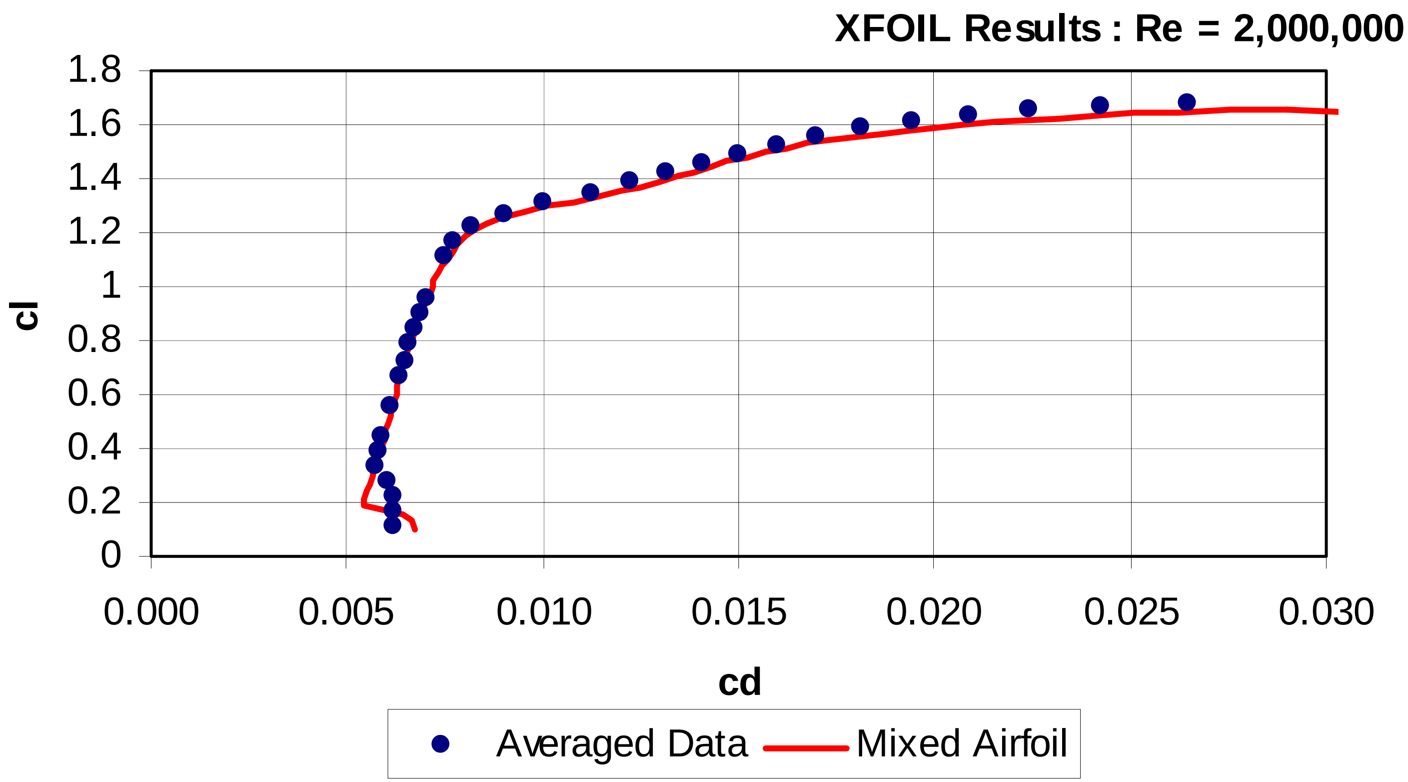
- Extrapolation below the lowest Reynolds number available in the airfoil data file(s) is difficult
  - Laminar separation effects can significantly alter the airfoil characteristics, particularly below 1,000,000
- Instead of having the code do the extrapolation, extrapolate the data manually if needed
  - Can inspect and modify the data before using it

Interpolated Airfoils

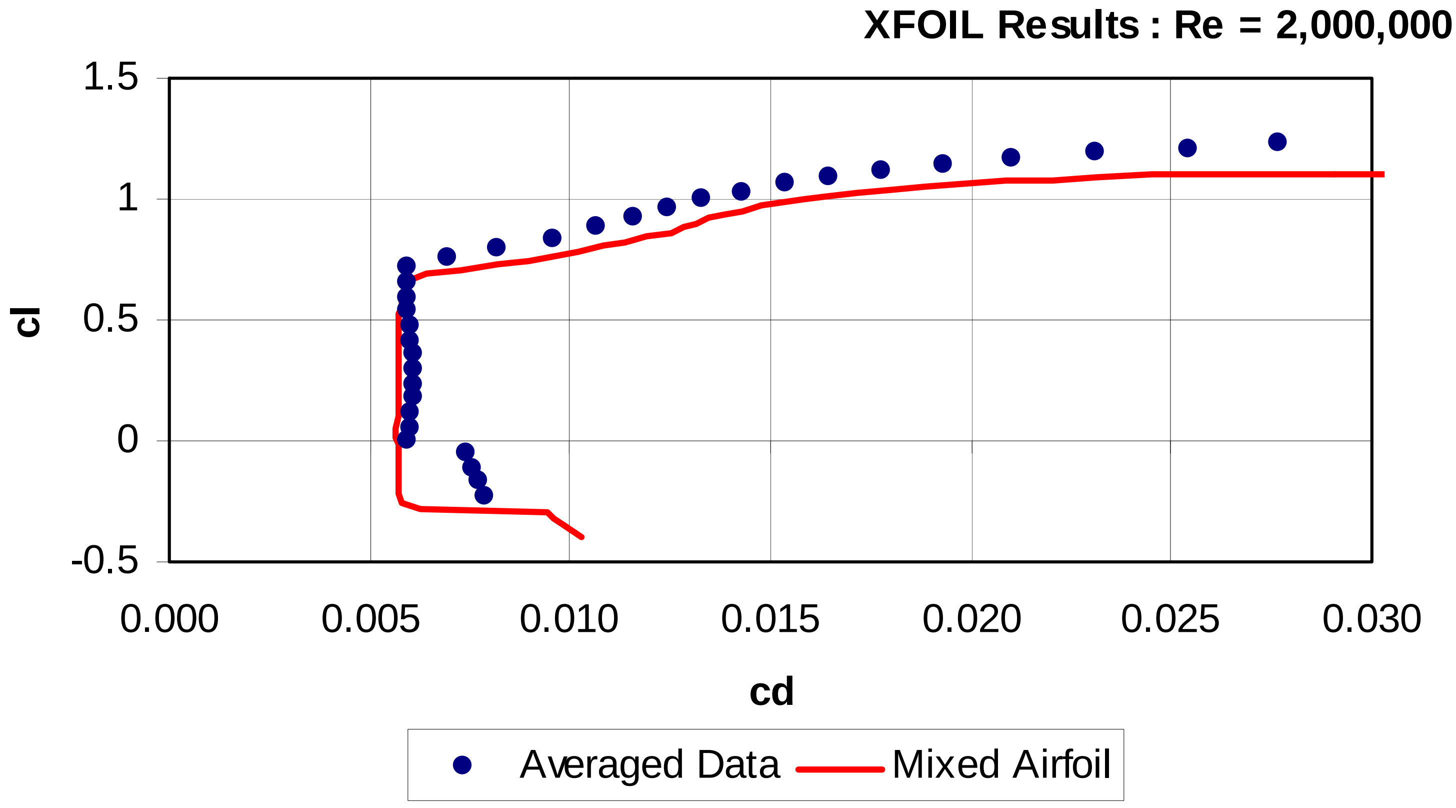
- Definition
  - Interpolated airfoils results from using more than one airfoil along the blade (often the case)
- PROPID Modeling of Interpolated Airfoils
  - Data of both “parent” airfoils are mixed to get the data of the interpolated airfoil
    - Linear transition
    - Non-linear transition using a blend function
  - How accurate is this method?

- Representative Cases
  - Case 1: S825/S826
    - Same C_{lmax} and similar t/c (17% vs 14%)
  - Case 2: S809/S810
    - Same C_{lmax} and similar t/c (21% vs 18%)
  - Case 3: S814/S825
    - Not same C_{lmax} nor thickness
  - All cases are a 50%–50% linear mix
  - Results generated using XFOIL for a Reynolds number of 2,000,000

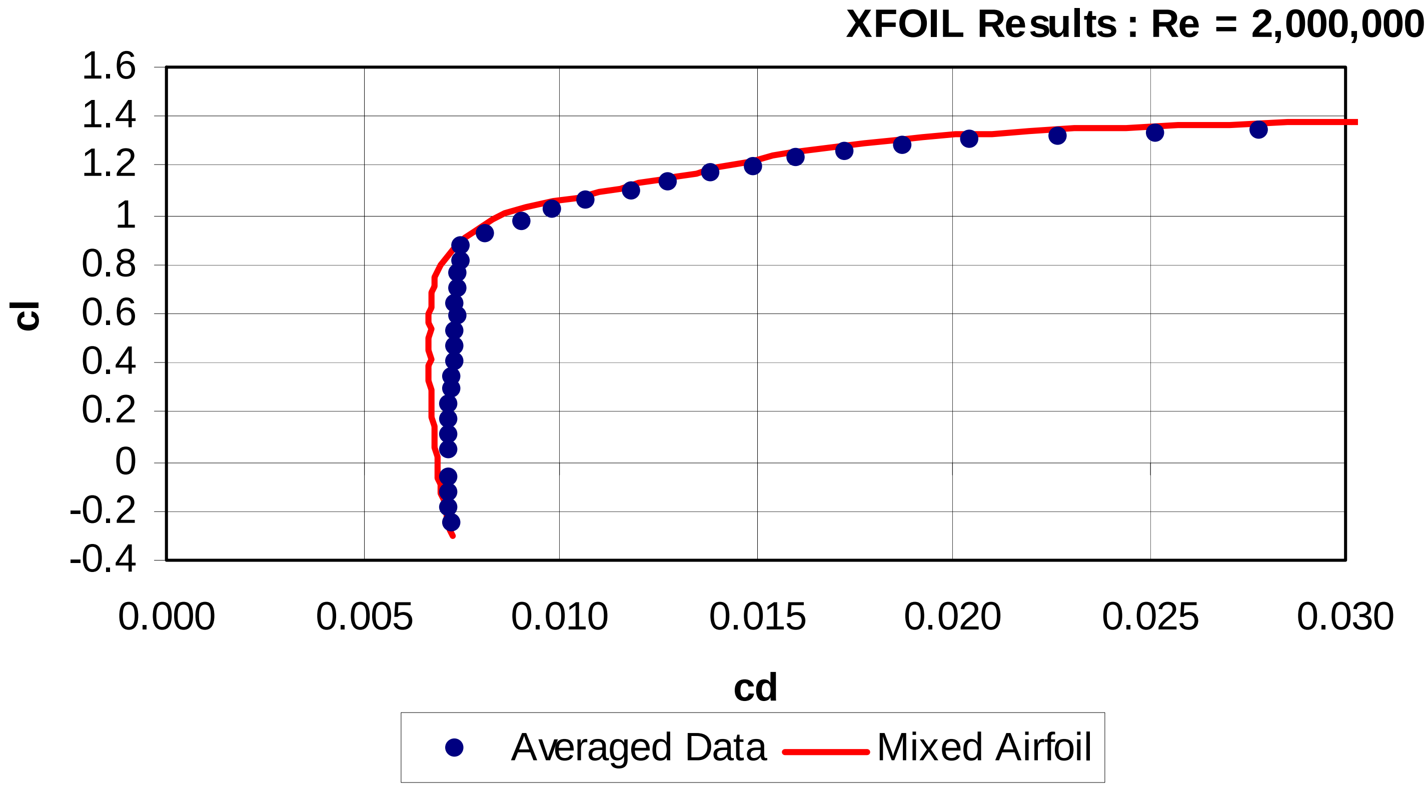
– Case 1: 50%–50% S825/S826



– Case 2: 50%–50% S809/S810



– Case 3: 50%–50% S814/S809



- Conclusions on Interpolated Airfoils
  - Similar C_{lmax} and t/c is not a necessary condition for good agreement
  - Similarities in shape and point of maximum thickness likely key for good agreement
  - Use as many “true” airfoils as possible, especially over the outboard section of the blade

Sources of Airfoil Data

- Wind Tunnel Testing
  - Airfoil tests sponsored by NREL
    - Delft University Low Turbulence Tunnel
      - S805, S809, and S814
      - Reynolds number range: 0.5 – 3 millions
      - Lift / drag: pressure dist. / wake rake
    - NASA Langley Low Turbulence Pressure Tunnel
      - S825 and S827
      - Reynolds number range: 1 – 6 millions
      - Lift / drag: pressure dist. / wake rake

- Ohio State University AARL 3’ x 5’ Tunnel
  - S805, S809, S814, S815, S825, and many more
  - Reynolds number range: 0.75 – 1.5 million
  - Lift / drag: pressure dist. / wake rake
- Penn State Low-Speed Tunnel
  - S805 and S824
  - Reynolds number range: 0.5 – 1.5 million
  - Lift / drag: pressure dist. / wake rake
- University of Illinois Subsonic Tunnel
  - S809, S822, S823, and many low Reynolds number airfoils
  - Reynolds number range: 0.1 – 1.5 million
  - Lift / drag: pressure dist. or balance / wake rake

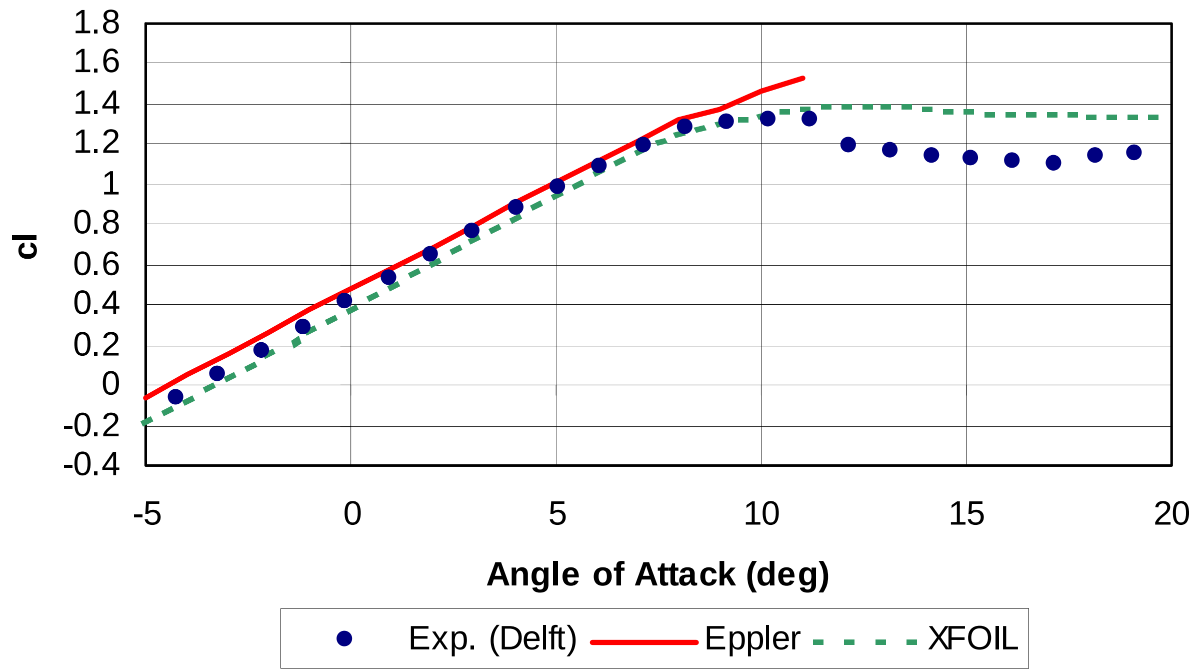
- Experimental methods used to simulate roughness effects
  - Trigger transition at leading edge using a boundary-layer trip (piece of tape) on upper and lower surface
  - Apply grit roughness around leading edge
    - More severe effect than trips

- Computational Methods for Airfoil Analysis
  - Eppler Code
    - Panel method with a boundary-layer method
    - For pricing contact: Dan Somers (Airfoils Inc.)
  - XFOIL
    - Panel method and viscous integral boundary-layer formulation with a user friendly interface
    - Open Source (free online)
    - Written by: Prof. Mark Drela, MIT
  - Both codes handle laminar separation bubbles and limited trailing-edge separation over a range of Reynolds numbers and Mach numbers

- Computational method used to simulate roughness effects
  - Fixed transition on upper and lower surface
    - Typically at 2%c on upper surface and 5%–10% on lower surface
    - Automatic switch to turbulent flow solver
    - Transition process not modeled
    - Device drag of roughness elements not modeled

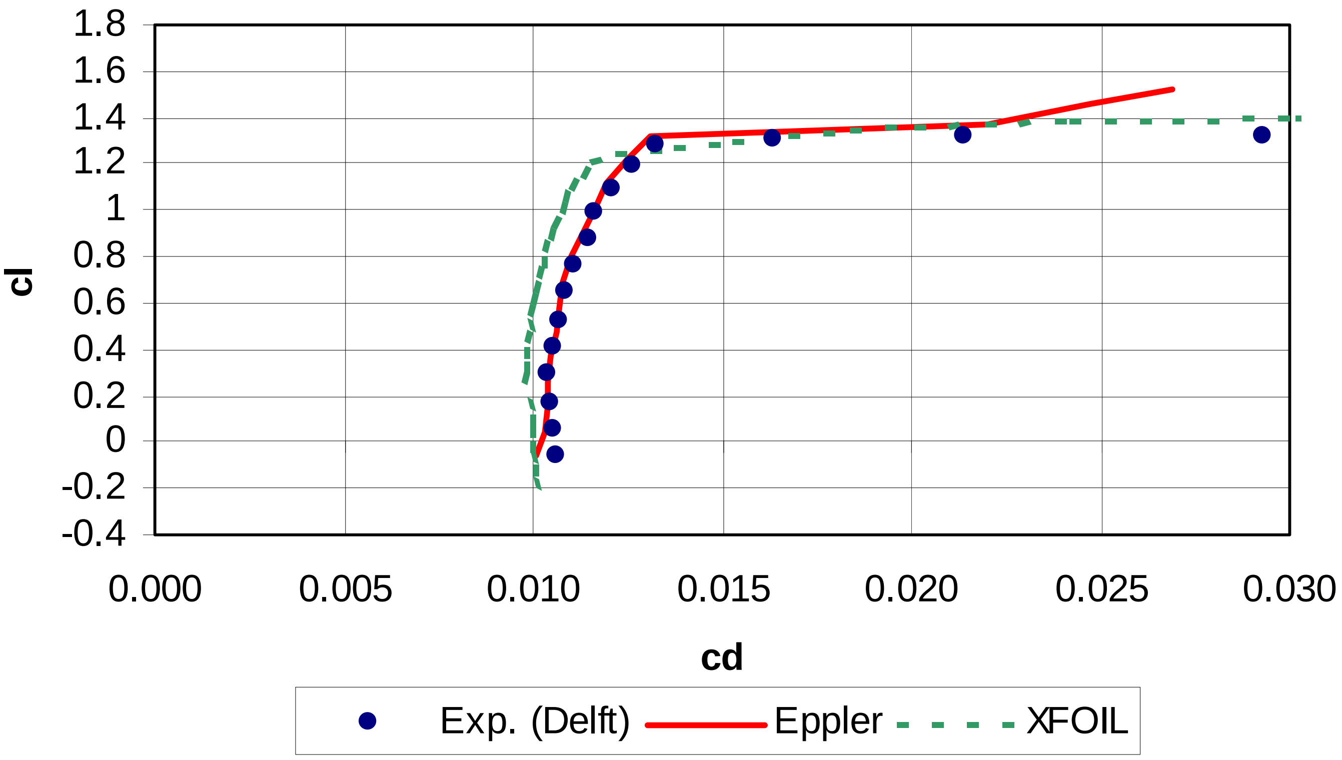
Computational vs Experimental Data

- Sample Results
  - S814 at a Reynolds number of 1,000,000 (clean)
    - Lift curve



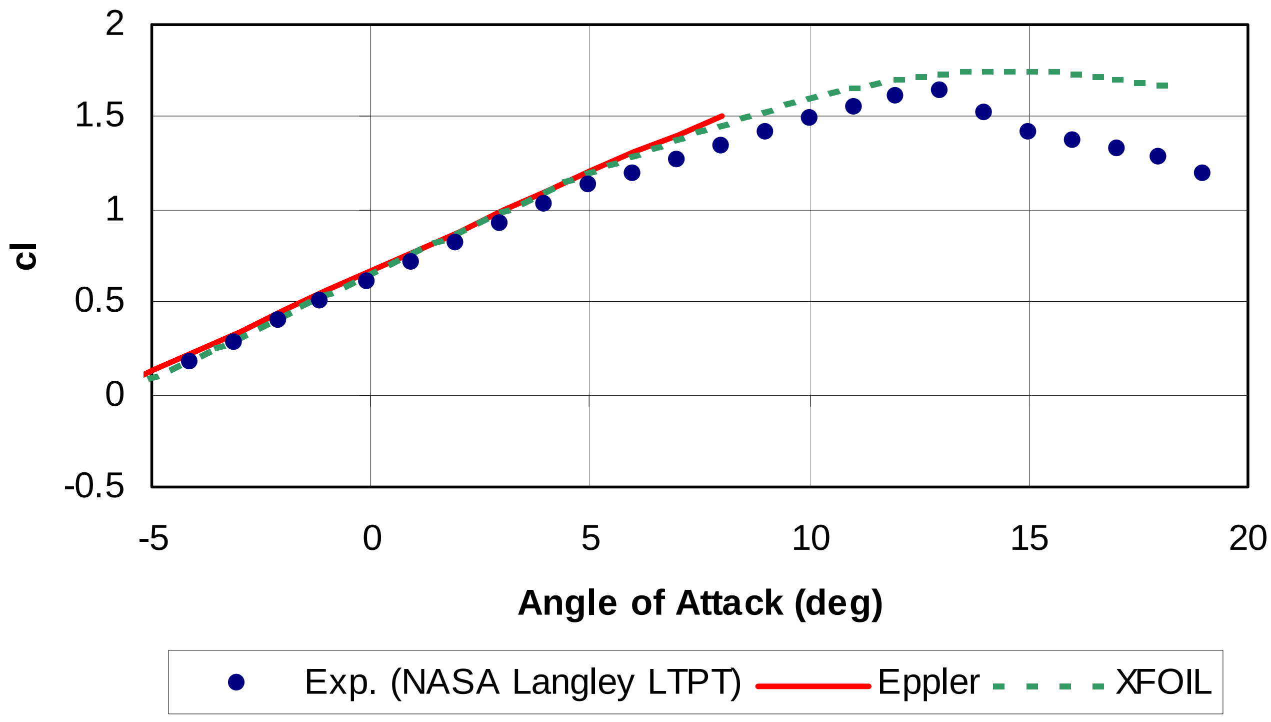
Note: results shown are not from the most recent version of the Eppler code

- Drag polar



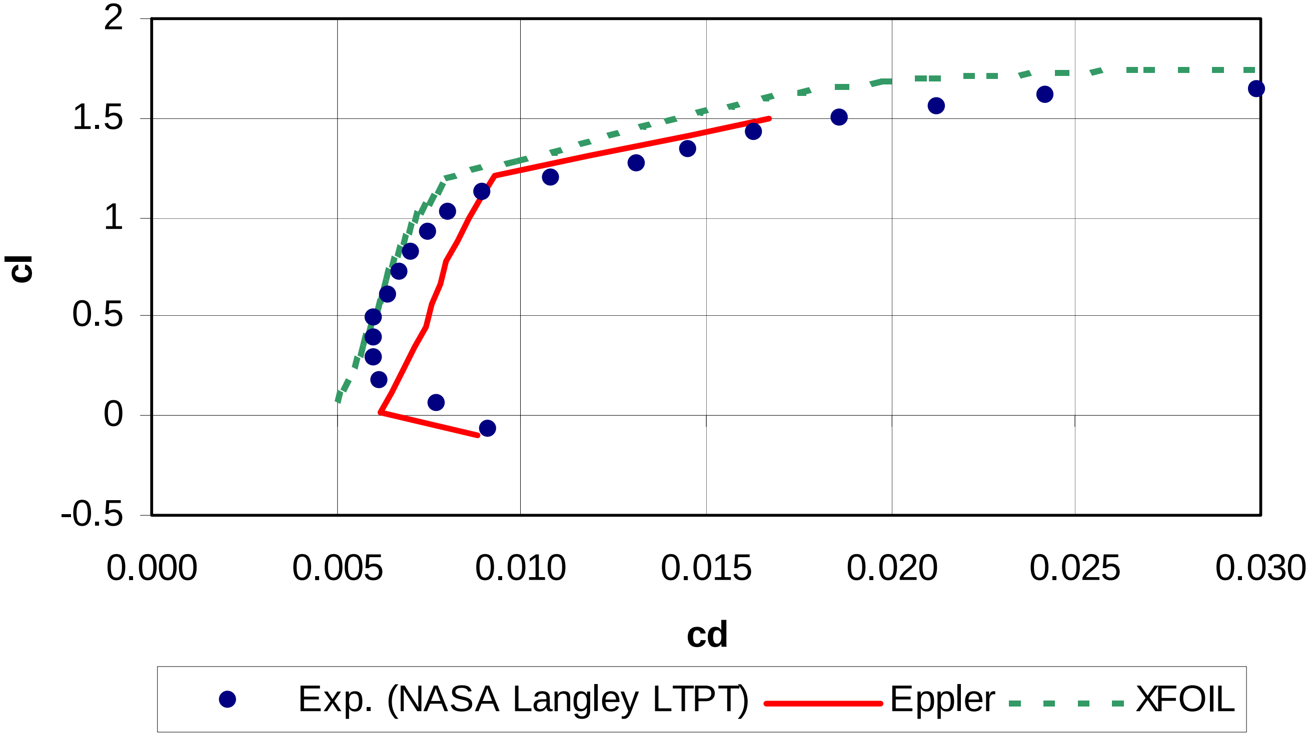
Note: results shown are not from the most recent version of the Eppler code

- S825 at a Reynolds number of 3,000,000 (clean)
  - Lift curve



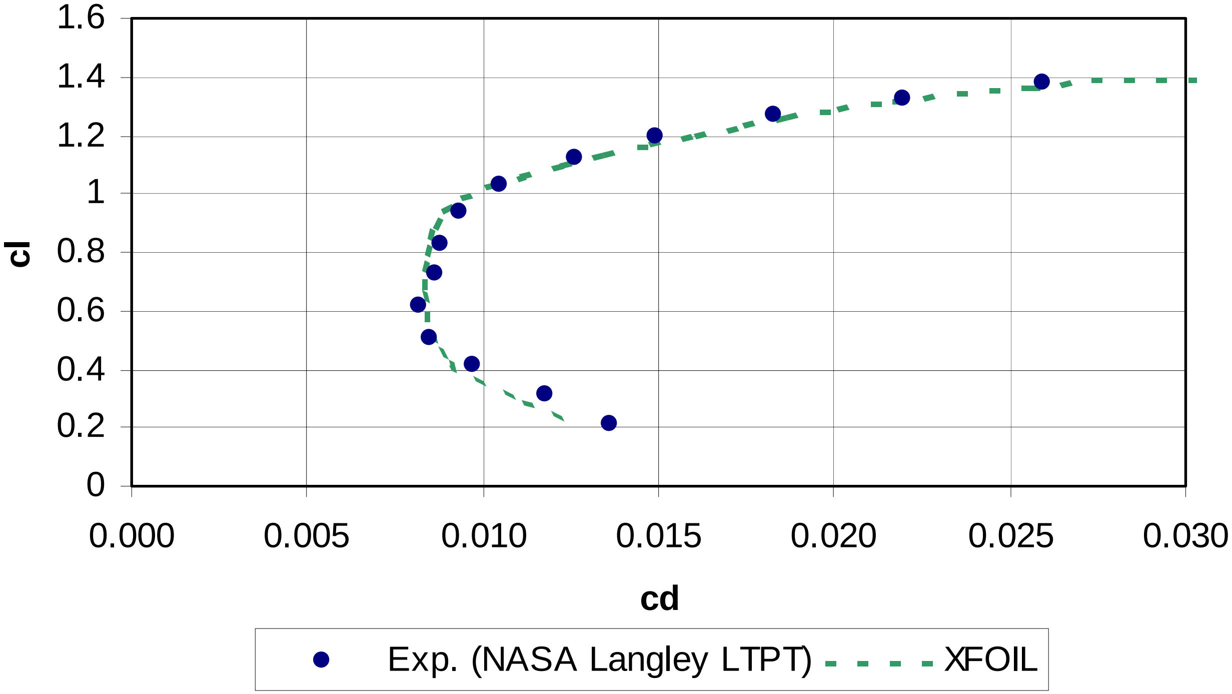
Note: results shown are not from the most recent version of the Eppler code

- Drag polar



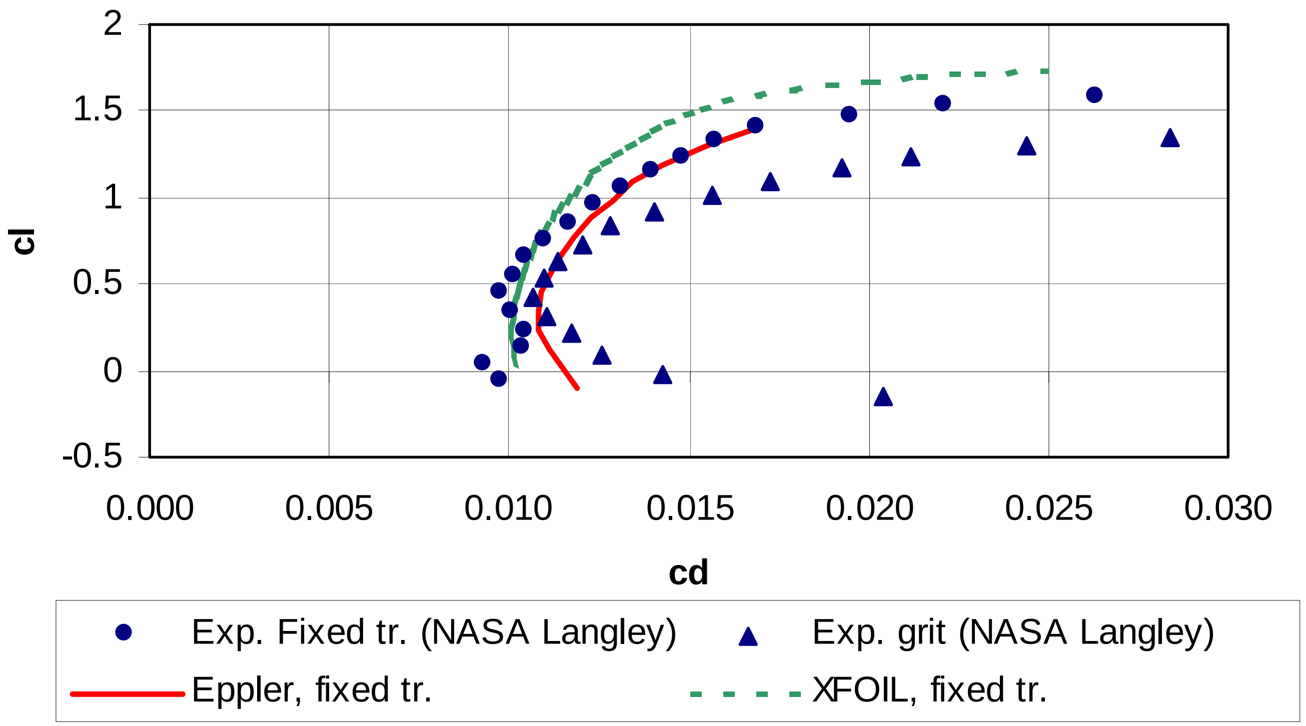
Note: results shown are not from the most recent version of the Eppler code

- SG6042 at a Reynolds number of 300,000 (clean)
  - Drag polar



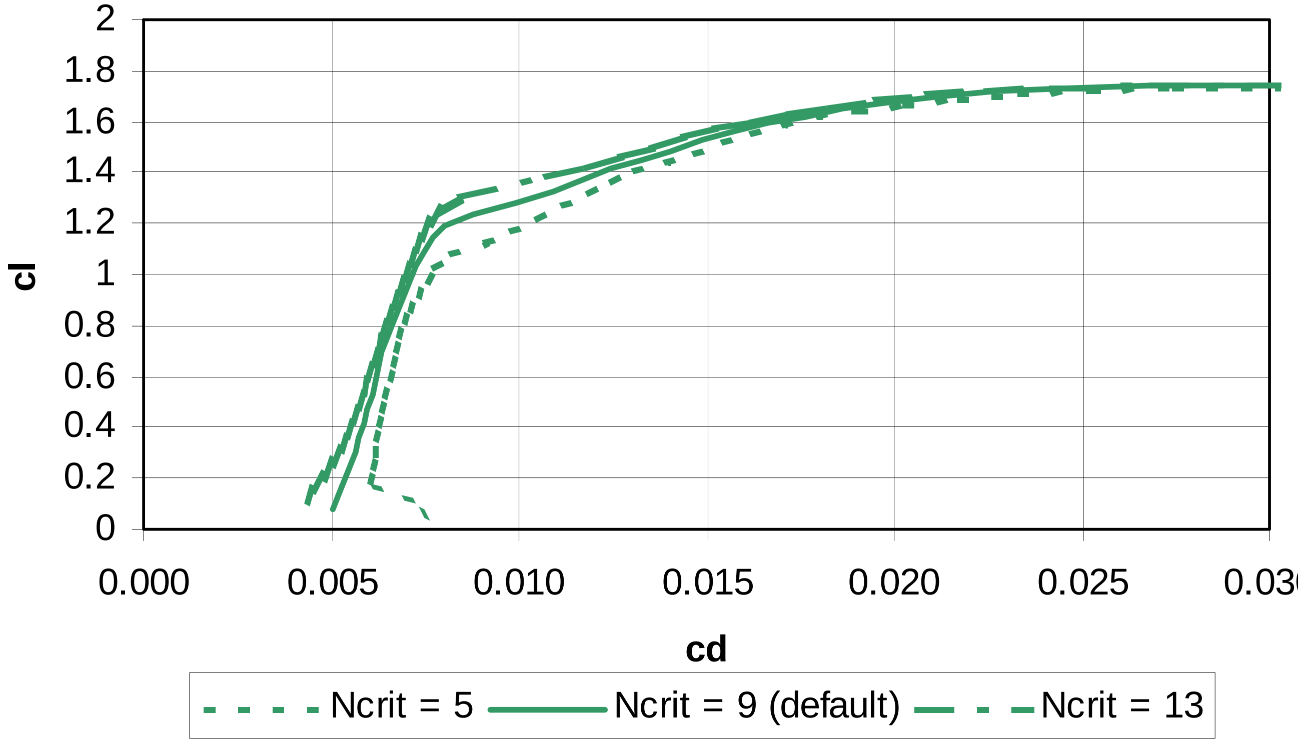
  - Agreement is not typically as good at lower Reynolds numbers than 300,000

- S825 at a Reynolds number of 3,000,000 (rough)
  - Drag polar



Note: results shown are not from the most recent version of the Eppler code

- Effect of the XFOIL parameter N_{crit} on Drag
  - S825 at a Reynolds number of 3,000,000 (clean)



  - N_{crit} related to turbulence level

- Conclusions on Experimental vs Computational Data
  - There are differences but trends are often captured
  - Computational data is an attractive option to easily obtain data for wind turbine design
  - Rely on wind tunnel tests data for more accurate analyses
    - C_{lmax}
    - Stall characteristics
    - Roughness effects
  - Both the Eppler code and XFOIL can be empirically "fine tuned" (XFOIL Parameter N_{crit})
  - Both methods continue to improve