Part I: Blade Design Methods and Issues

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

Outline

- Survey of Steady-Aerodynamics Codes
- Blade Design Trade-Offs and Issues
- Wind Turbine Airfoils
- Noise Sources and Tip Shapes
- Stall-Delay Models

Survey of Steady-Aerodynamics Codes

- Historical Development of BEMT Performance and Design Methods in the US
  - Summary

Year	Codes	Developers
1974	PROP	Wilson and Walker
1981	WIND	Snyder
1983	Revised PROP	Hibbs and Radkey
	PROPSH	Tangler
	WIND-II	Snyder and Staples
1984	PROPFILE	Fairbank and Rogers

Year	Code	Developer
1986	NUPROP	Hibbs
1987	PROPPC	Kocurek
1993	PROP93	McCarty
1994	PROPID	Selig
1995	WIND-III	Huang and Miller
	PROPGA	Selig and Coverstone-Carroll
1996	WT_PERF	Buhl
1998	PROP98	Combs
2000	New PROPGA	Giguère

– Some details of each code

1974

PROP
- Fortran 77

1981

WIND
- Based on PROP code
- Accounts for spoilers, ailerons, and other airfoil modifications

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1983

Revised PROP
- Windmill brake state
- Wind shear effects
- Flat-plate post-stall airfoil characteristics

1983 continue

PROPSH

– Rotor shaft tilt option
– Dimensional outputs

WIND-II

– Empirical axial induction models
– 2D airfoil data
– Energy computation

1984

PROPFILE

– PC version of PROPSH

1986

NUPROP

- Dynamic stall
- Wind shear
- Tower shadow
- Yaw error
- Large scale turbulence

1987

PROPPC

- PC version of PROP

1993

PROP93

- PROP with graphical outputs
- Programmed in C

1994

PROPID

- Inverse design method
- Airfoil data interpolation
- Improved tip-loss model

1995

WIND-III

- PC version of WIND-II
- Accounts for various aero breaking schemes

PROPGA

- Genetic-algorithm based optimization method
- Optimize for max. energy
- Uses PROPID

1996

WT_PERF

- Improved tip-loss model
- Drag term in calculating inplane induced velocities
- Fortran 90

1998

PROP98

- Enhanced graphics
- Windows Interface

2000

New PROPGA

- Structural and cost considerations
- Airfoil selection
- Advanced GA operators
- Multi objectives

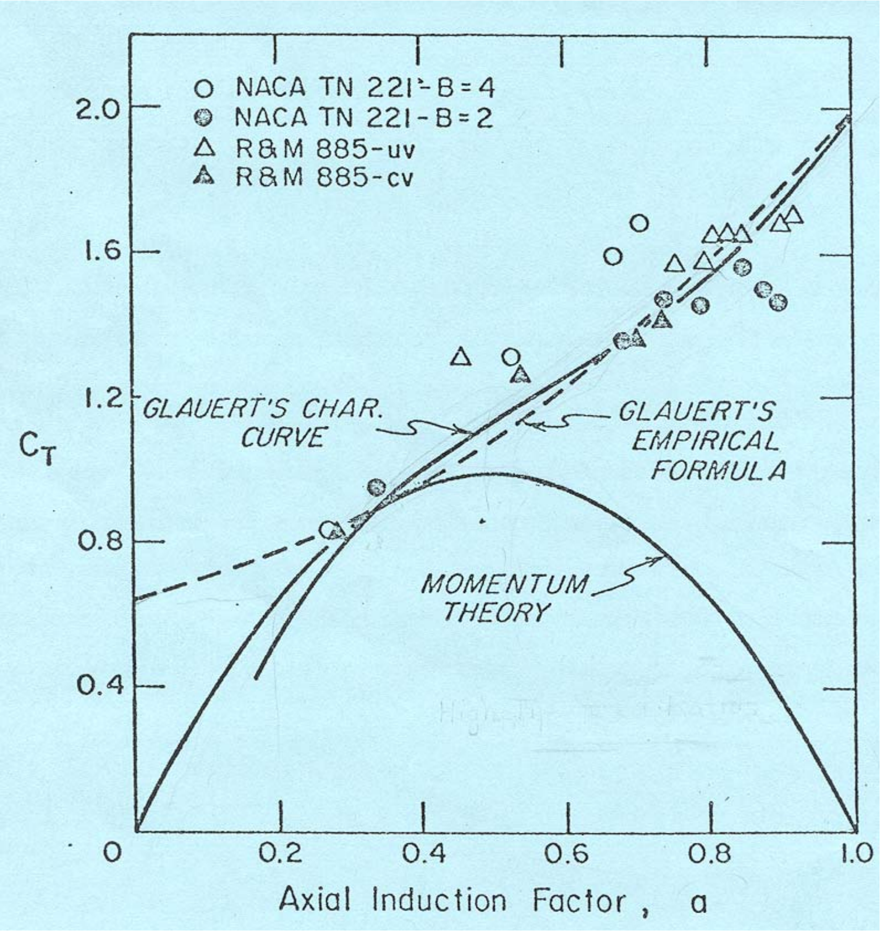
- Types of Steady-State BEMT Performance and Design Methods

Analysis	Inverse Design	Optimization
PROP	PROPID	PROPGA
WIND		
Revised PROP		
PROPSH		
WIND-II		
PROPFILE		
NUPROP		
PROPPC		
PROP93		
WIND-III		
WT_PERF		
PROP98		

- Features of Selected Performance and Design Codes

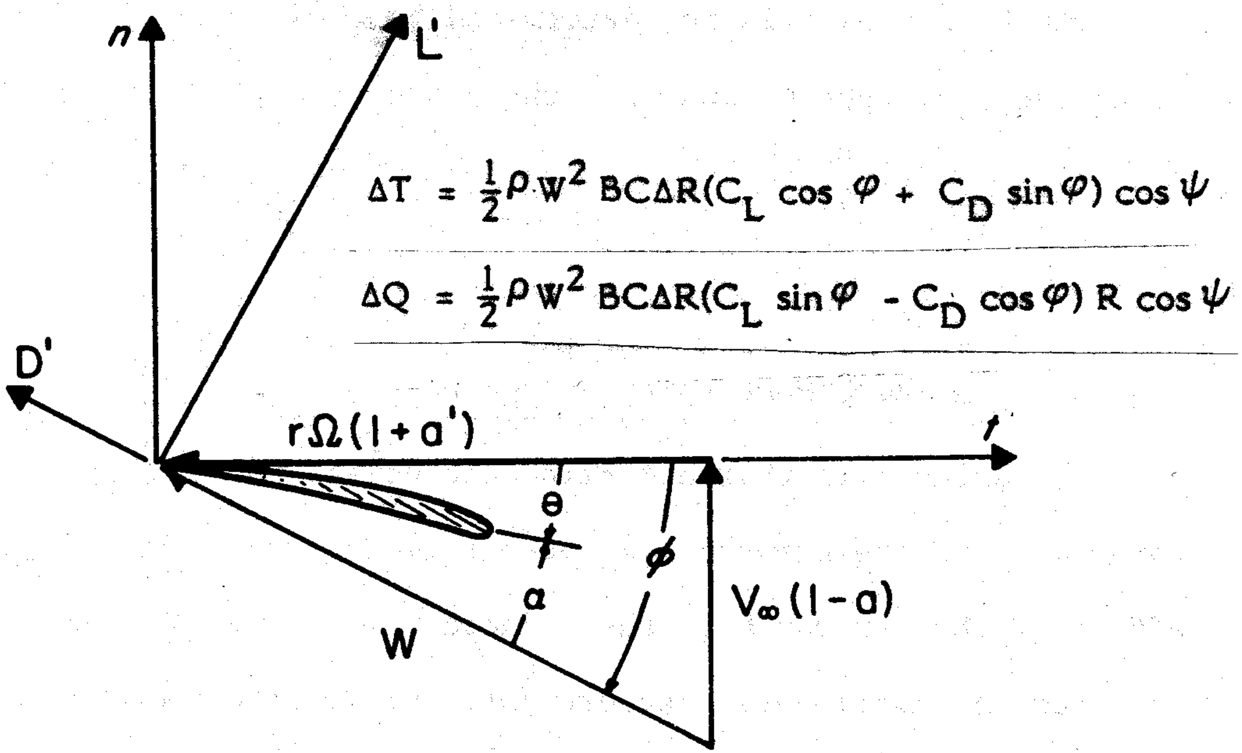
CODES Features	**PROPPC** **WT-Perf** AeroVironment NREL	**NUPROP** AeroVironment	**PROP93** AEI	**PROPID** Univ. of Illinois
Development Date	1987	1986	1993	1997
Airfoil Data Interpolation	no	no	no	yes
3-D Stall Delay	no	no	no	yes
Glauert Approximation	yes	yes	yes	yes
Tip Losses	yes	yes	yes	yes
Windspeed Sweep	yes	yes	yes	yes
Pitch Sweep	yes	yes	yes	yes
Shaft Tilt	yes	yes	yes	yes
Yaw Angle	no	yes	yes	yes
Tower Shadow	no	yes	no	yes
Dynamic Stall	no	yes	no	no
Graphics	no	no	yes	no
Program Language	Fortran	Fortran	C	Fortran
Other		turbulence	hub ext.	Inverse design
Cost	free	free	$50	free

- Glauert Correction for the Viscous Interaction
  - less induced velocity
  - greater angle of attack
  - more thrust and power



- Prediction Sources of Error
  - Airfoil data
    - Correct Reynolds number
    - Post-stall characteristics
  - Tip-loss model
  - Generator slip RPM change

- How Is Lift and Drag Used?
  - Only lift used to calculate the axial induction factor **a**
  - Both lift and drag used to calculate the swirl **a'**



- Designing for Steady-State Performance vs Performance in Stochastic Wind Environment
  - Turbulence
  - Wind shear
  - Dynamic stall
  - Yaw error
  - Elastic twist
  - Blade roughness

Blade Design Trade-offs and Issues

- Aerodynamics vs Stuctures vs Dynamics vs Cost
  - The aerodynamicists desire thin airfoils for low drag and minimum roughness sensitivity
  - The structural designers desire thick airfoils for stiffness and light weight
  - The dynamicists desires depend on the turbine configuration but often prefer airfoils with a soft stall, which typically have a low to moderate C_{lmax}
  - The accountant wants low blade solidity from high C_{lmax} airfoils, which typically leads to lower blade weight and cost

- Low-Lift vs High-Lift Airfoils
  - Low-lift implies larger blade solidity, and thus larger extreme loads
  - Extreme loads particularly important for large wind turbines
  - Low-lift airfoils have typically a soft stall, which is dynamically beneficial, and reduce power spikes
  - High-lift implies smaller chord lengths, and thus lower operational Reynolds numbers and possible manufacturing difficulties
  - Reynolds number effects are particularly important for small wind turbines

- Optimum Rotor Solidity
  - Low rotor solidity often leads to low blade weight and cost
  - For a given peak power, the optimum rotor solidity depends on:
    - Rotor diameter (large diameter leads to low solidity)
    - Airfoils (e.g., high c_{lmax} leads to low solidity)
    - Rotor rpm (e.g., high rpm leads to low solidity)
    - Blade material (e.g, carbon leads to low solidity)
  - For large wind turbines, the rotor or blade solidity is limited by transportation constraints

- Swept Area (2.2 - 3.0 m^2/kW)
  - Generator rating
  - Site dependent
- Blade Flap Stiffness ($\sim t^2$)
  - Airfoils
  - Flutter
  - Tower clearance

- Rotor Design Guidelines
  - Tip speed: < 200 ft/sec (61 m/sec)
  - Swept area/power: wind site dependent
  - Airfoils: need for higher-lift increases with turbine size, weight. & cost ~ $R^{2.8}$
  - Blade stiffness: airfoil thickness ~ t^2
  - Blade shape: tapered/twisted vs constant chord
  - Optimize c_p for a blade tip pitch of 0 to 4 degrees with taper and twist

Wind Turbine Airfoils

- Design Perspective
  - The environment in which wind turbines operate and their mode of operation not the same as for aircraft
    - Roughness effects resulting from airborne particles are important for wind turbines
    - Larger airfoil thicknesses needed for wind turbines
  - Different environments and modes of operation imply different design requirements
  - The airfoils designed for aircraft not optimum for wind turbines

- Design Philosophy
  - Design specially-tailored airfoils for wind turbines
    - Design airfoil families with decreasing thickness from root to tip to accommodate both structural and aerodynamic needs
    - Design different families for different wind turbine size and rotor rigidity

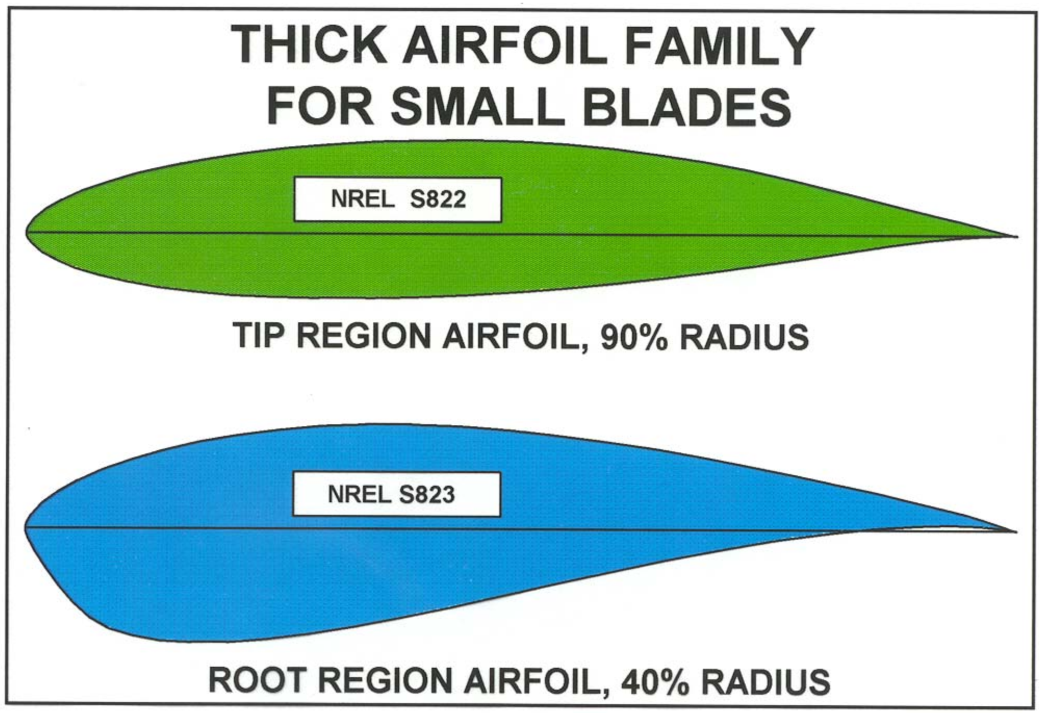
- Main Airfoil Design Parameters
  - Thickness, t/c
  - Lift range for low drag and C_{lmax}
  - Reynolds number
  - Amount of laminar flow

- Design Criteria for Wind Turbine Airfoils
  - Moderate to high thickness ratio t/c
    - Rigid rotor: 16%–26% t/c
    - Flexible rotor: 11%–21% t/c
    - Small wind turbines: 10%-16% t/c
  - High lift-to-drag ratio
  - Minimal roughness sensitivity
  - Weak laminar separation bubbles

- NREL Advanced Airfoil Families

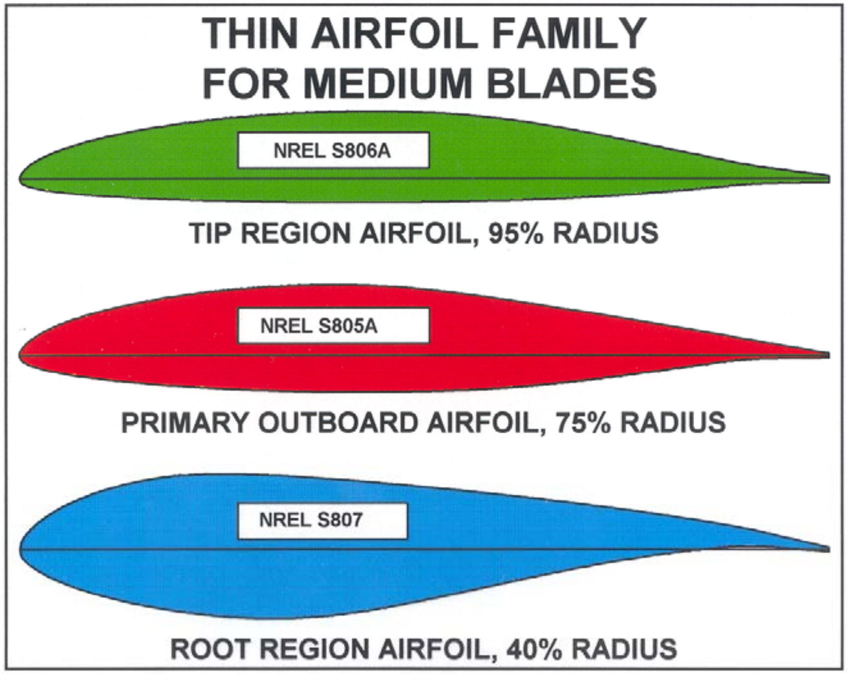
Blade Length (meters)	Generator Size (kW)	Thickness Category	Airfoil Family (root--------------------------------tip)			
1-5	2-20	thick		S823		S822
5-10	20-150	thin		S804	S801	S803
5-10	20-150	thin	S808	S807	**S805A**	S806A
5-10	20-150	thick		S821	S819	S820
10-15	150-400	thick	S815	**S814**	**S809**	S810
10-15	150-400	thick	S815	**S814**	S812	S813
15-25	400-1000	thick		S818	S816	S817
15-25	400-1000	thick		S818	**S825**	S826

Note: Shaded airfoils have been wind tunnel tested.



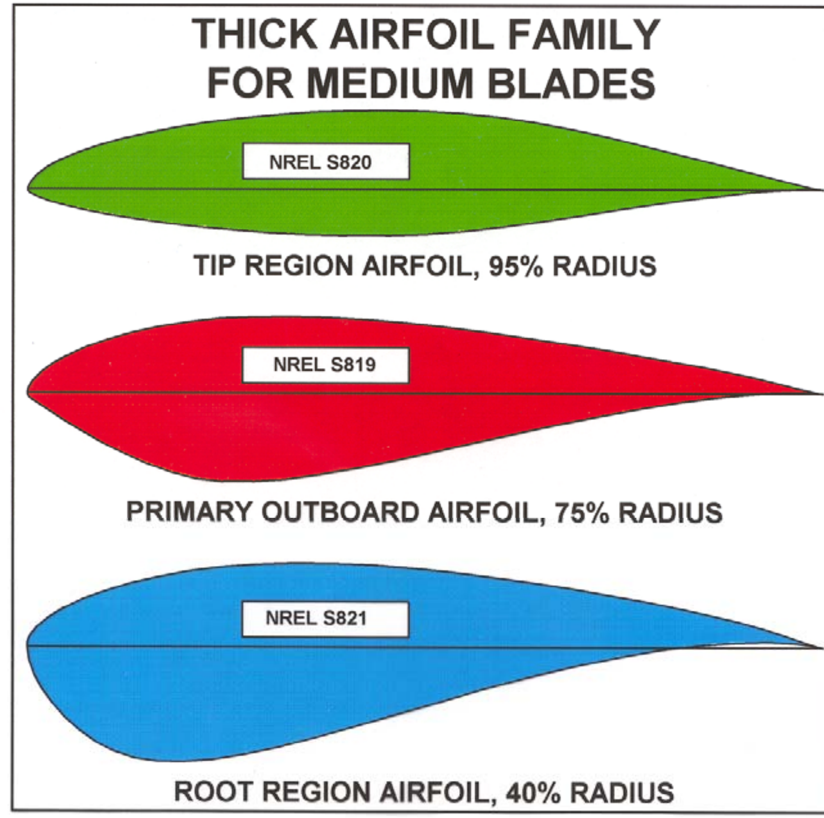
Design Parameters

Airfoil	r/R	Re. No. ($x10^6$)	t/c	C_{lmax}	C_{dmin}	C_{mo}
S822	0.90	0.6	0.160	1.00	0.010	-0.07
S823	0.40	0.4	0.240	1.30	0.018	-0.15



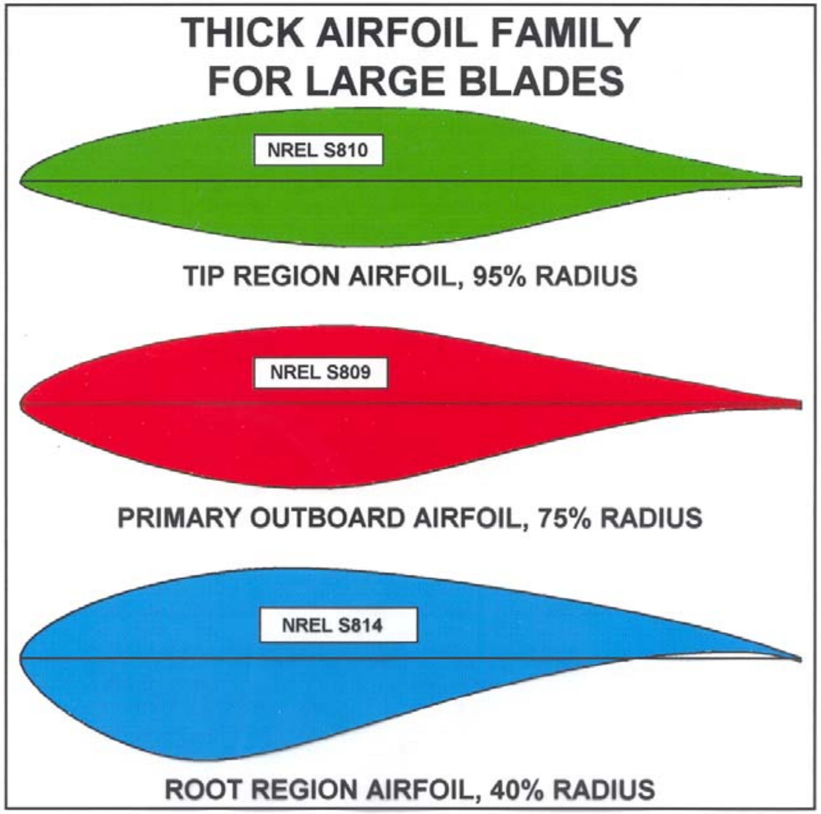
Design Parameters

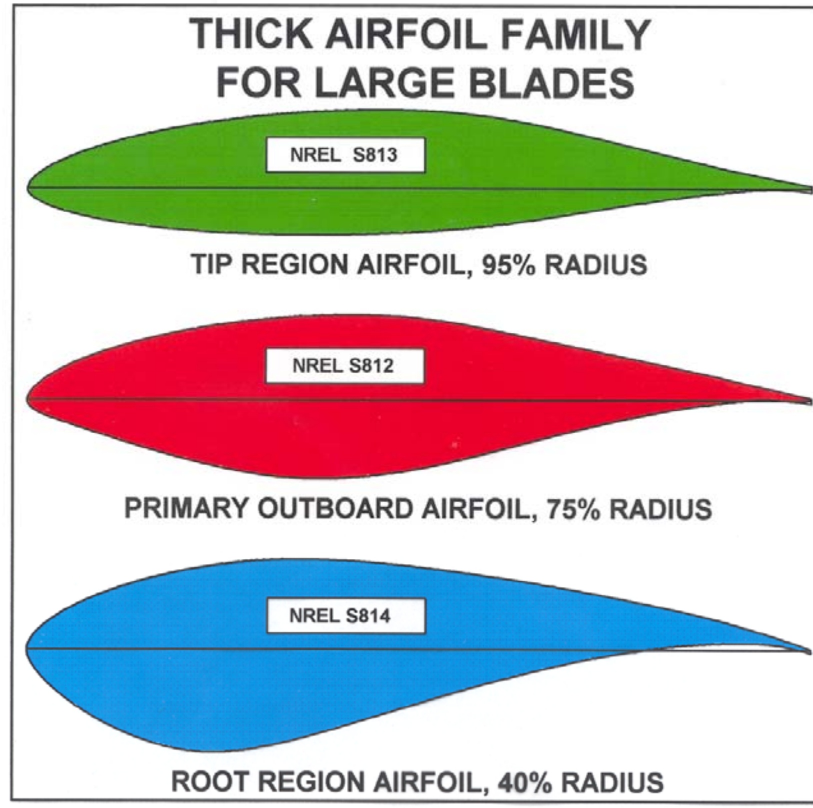
Airfoil	r/R	Re. No. ($x10^6$)	t/c	C_{lmax}	C_{dmin}	C_{mo}
S806A	0.95	1.3	0.115	1.10	0.004	-0.05
S805A	0.75	1.0	0.135	1.20	0.005	-0.05
S807	0.40	0.8	0.180	1.46	0.010	-0.10
S808	0.30	0.8	0.210	1.30	0.012	-0.12



Design Parameters

Airfoil	r/R	Re. No. ($x10^6$)	t/c	C_{lmax}	C_{dmin}	C_{mo}
S820	0.95	1.3	0.160	1.10	0.007	-0.07
S819	0.75	1.0	0.210	1.20	0.008	-0.07
S821	0.40	0.8	0.240	1.40	0.014	-0.15



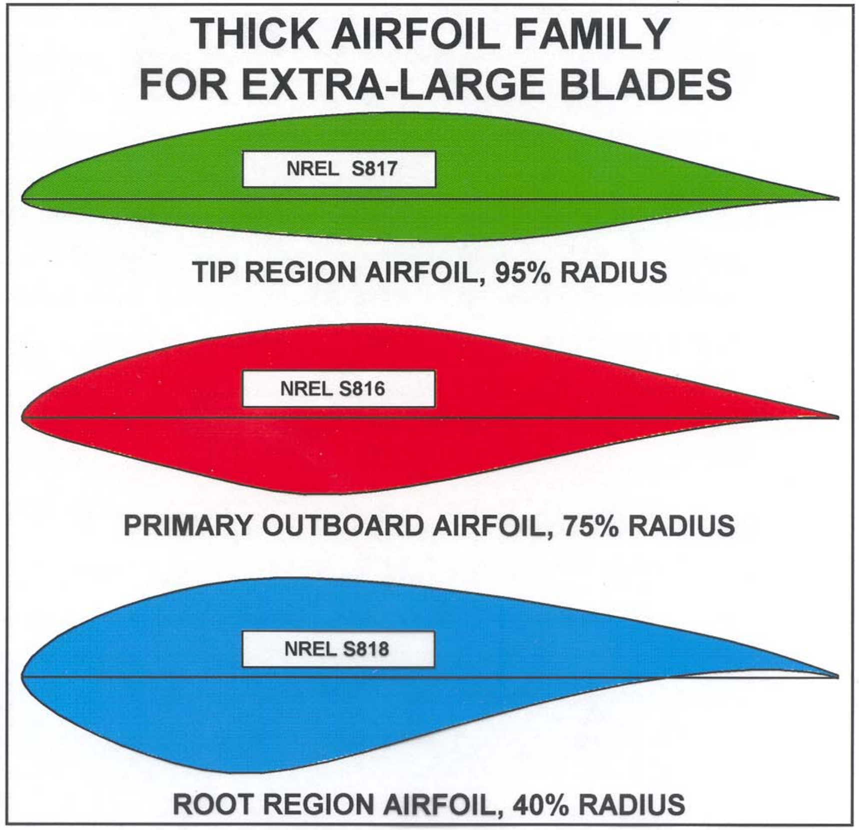


Design Parameters

Airfoil	r/R	Re. No. ($x10^6$)	t/c	C_{lmax}	C_{dmin}	C_{mo}
S810	0.95	2.0	0.180	0.90	0.006	-0.05
S809	0.75	2.0	0.210	1.00	0.007	-0.05
S814	0.40	1.5	0.240	1.30	0.012	-0.15
S815	0.30	1.2	0.260	1.10	0.014	-0.15

Design Parameters

Airfoil	r/R	Re. No. ($x10^6$)	t/c	C_{lmax}	C_{dmin}	C_{mo}
S813	0.95	2.0	0.160	1.10	0.007	-0.07
S812	0.75	2.0	0.210	1.20	0.008	-0.07
S814	0.40	1.5	0.240	1.30	0.012	-0.15
S815	0.30	1.2	0.260	1.10	0.014	-0.15



Design Parameters

Airfoil	r/R	Re. No. ($x10^6$)	t/c	C_{lmax}	C_{dmin}	C_{mo}
S817	0.95	3.0	0.160	1.10	0.007	-0.07
S816	0.75	4.0	0.210	1.20	0.008	-0.07
S818	0.40	2.5	0.240	1.30	0.012	-0.15

– Potential Energy Improvements

- NREL airfoils vs airfoils designed for aircraft (NACA)

Turbine Type	Roughness Insensitive $c_{l,max}$, c_l	Correct Reynolds No, Thickness	Low Tip $c_{l,max}$	Total Improvement
Stall-Regulated	10% to 15%	3% to 5%	10% to 15%	23% to 35%
Variable-Pitch	5% to 15%	3% to 5%	---	8% to 20%
Variable-RPM	5%	3% to 5%	---	8% to 10%

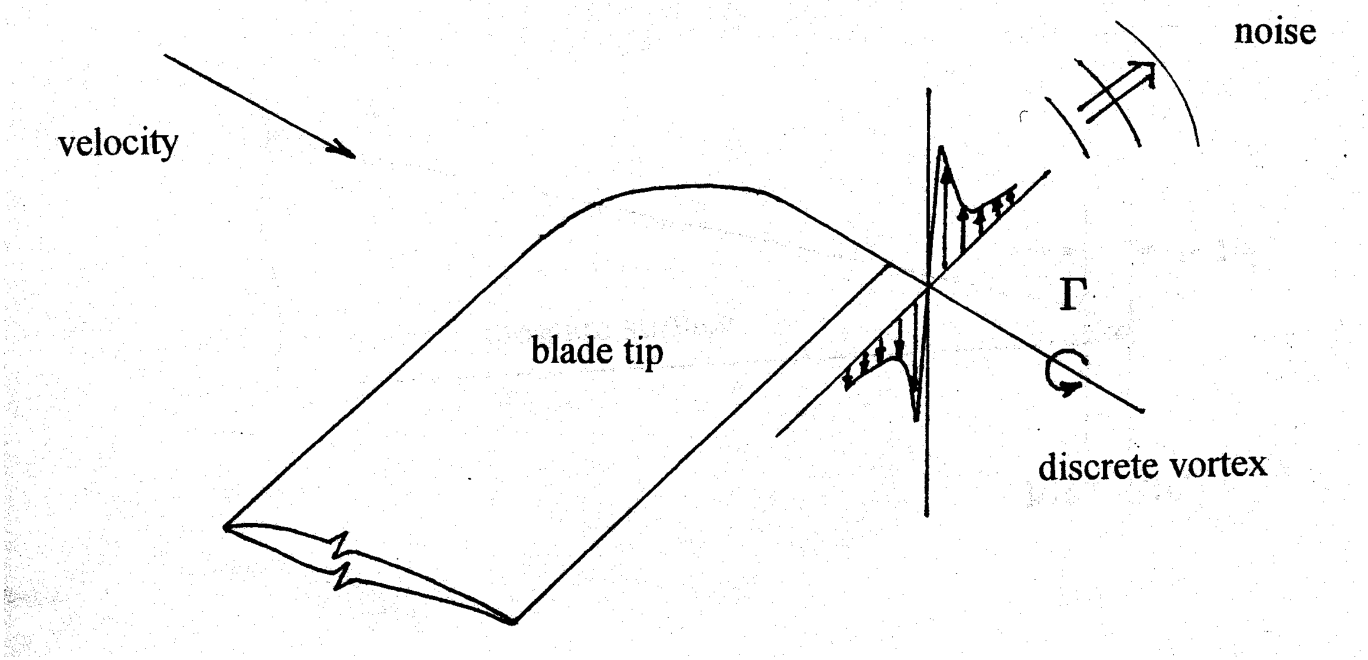
- Other Wind Turbine Airfoils
  - University of Illinois
    - SG6040/41/42/43 and SG6050/51 airfoil families for small wind turbines (1-10 kW)
    - Numerous low Reynolds number airfoils applicable to small wind turbines
  - Delft (Netherlands)
  - FFA (Sweden)
  - Risø (Denmark)

- Airfoil Selection
  - Appropriate design Reynolds number
  - Airfoil thickness according to the amount of centrifugal stiffening and desired blade rigidity
  - Roughness insensitivity most important for stall regulated wind turbines
  - Low drag not as important for small wind turbines because of passive over speed control and smaller relative influence of drag on performance
  - High-lift root airfoil to minimize inboard solidity and enhanced starting torque

Noise Sources and Tip Shapes

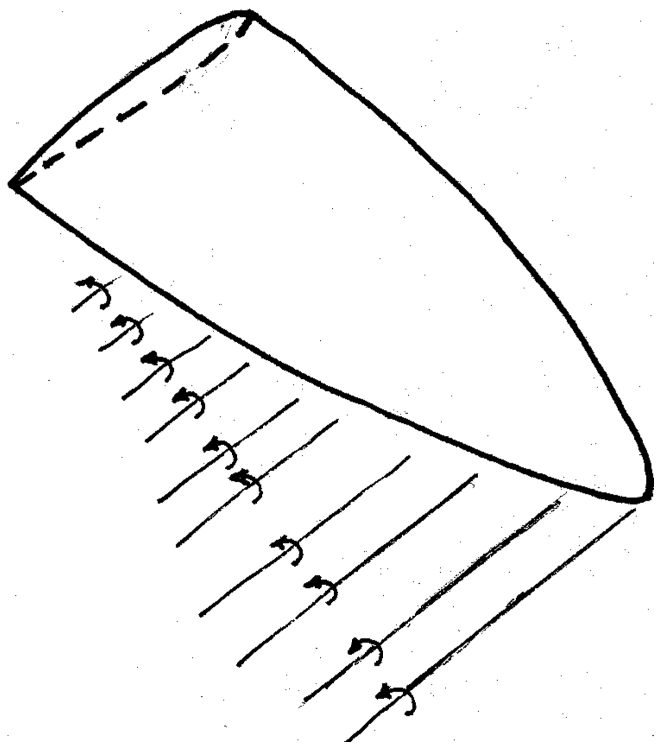
- Noise Sources
  - Tip-Vortex / Trailing-Edge Interaction
  - Blade/Vortex Interaction
  - Laminar Separation Bubble Noise

- Tip-Vortex / Trailing-Edge Interaction

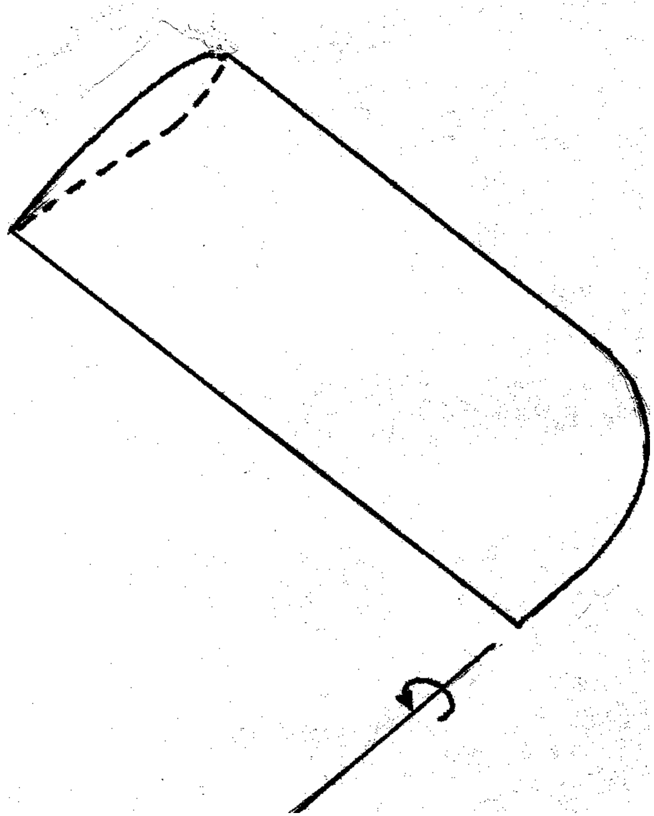


- Tip Shapes

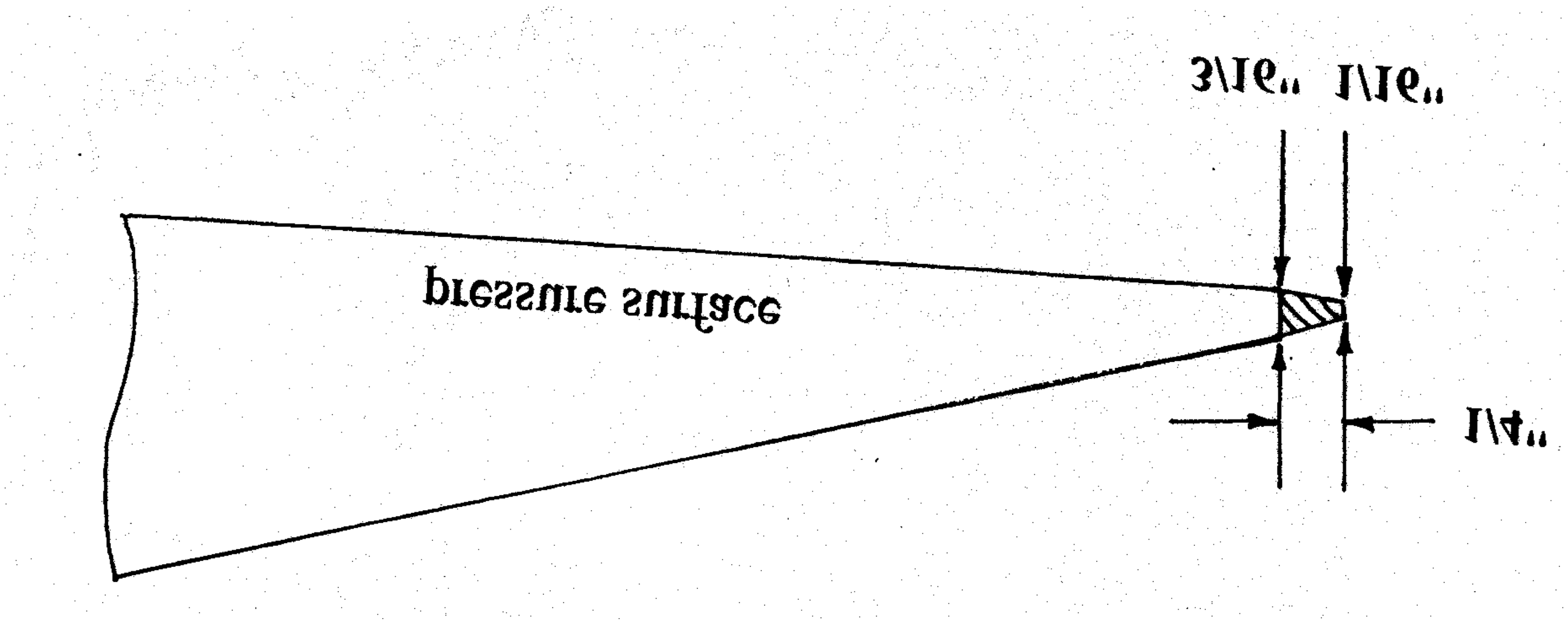
Sword Shape



Swept Tip

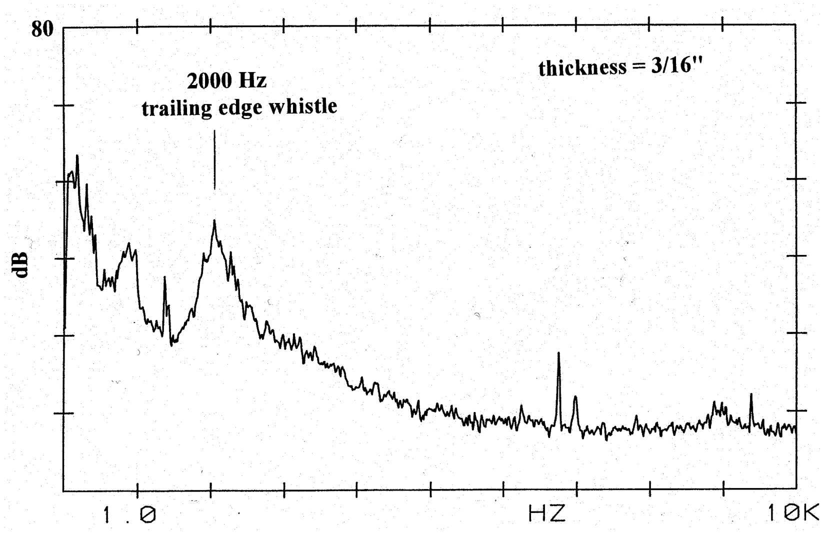


- Effect of Trailing-Edge Thickness at the Tip of the Blade

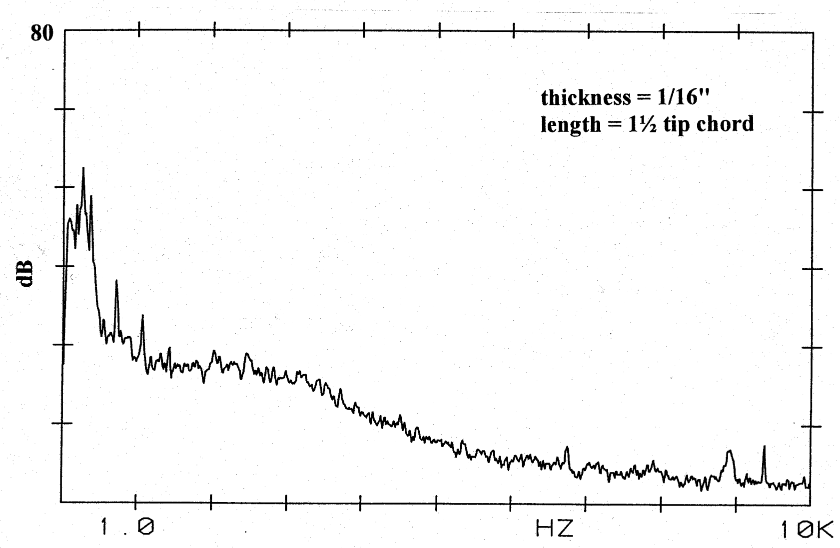


- Thick and Thin Trailing Edge Noise Measurements

Thick Tip trailing Edge



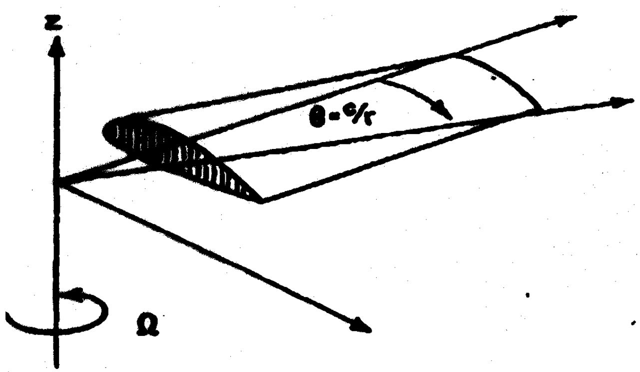
Thin Tip Trailing Edge



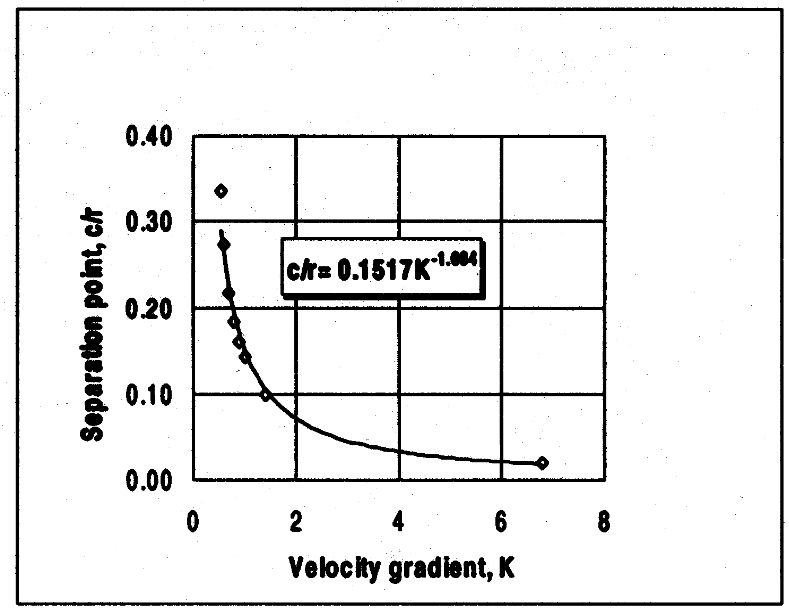
Stall-Delay and Post-Stall Models

- Stall-Delay Models
  - Viterna
  - Corrigan & Schillings
  - UIUC model

- Corrigan & Schillings Stall-Delay Model
  - Simplified equations

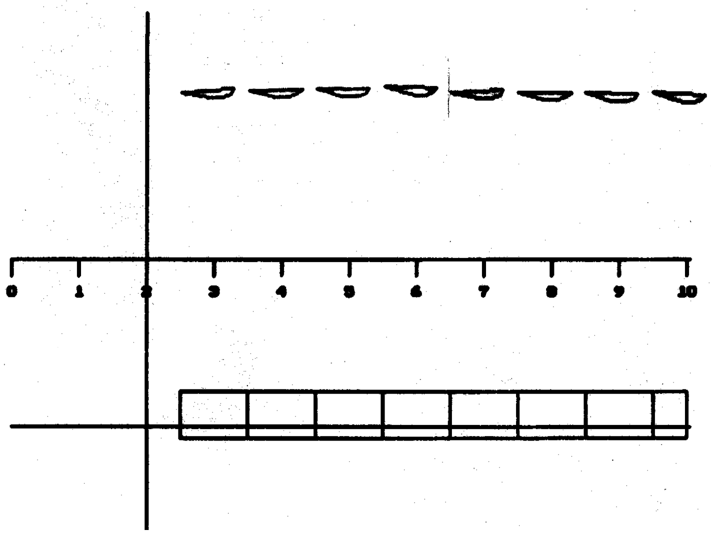


$$\Delta\alpha = \left(\alpha_{C_{l,max}} - \alpha_{C_{l=0}}\right)\left[\left(\frac{K\theta_{TE}}{0.136}\right)^n - 1\right]$$

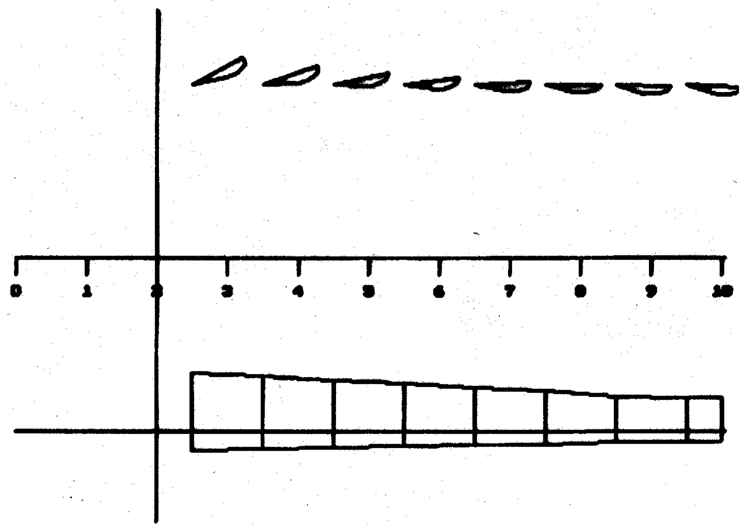


– CER blade geometry

- **constant-chord blade**



- **tapered-chord blade**



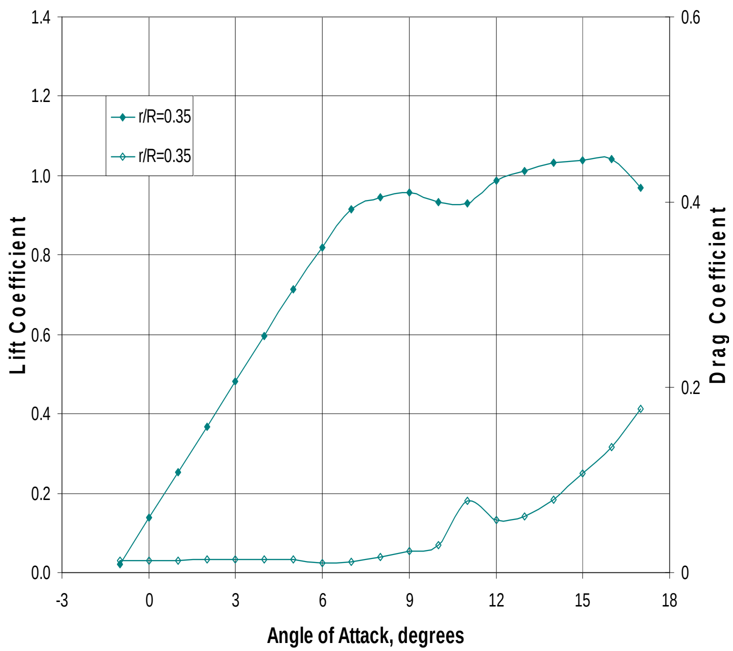
- Examples
  - CER1 Constant chord/non-twist blade

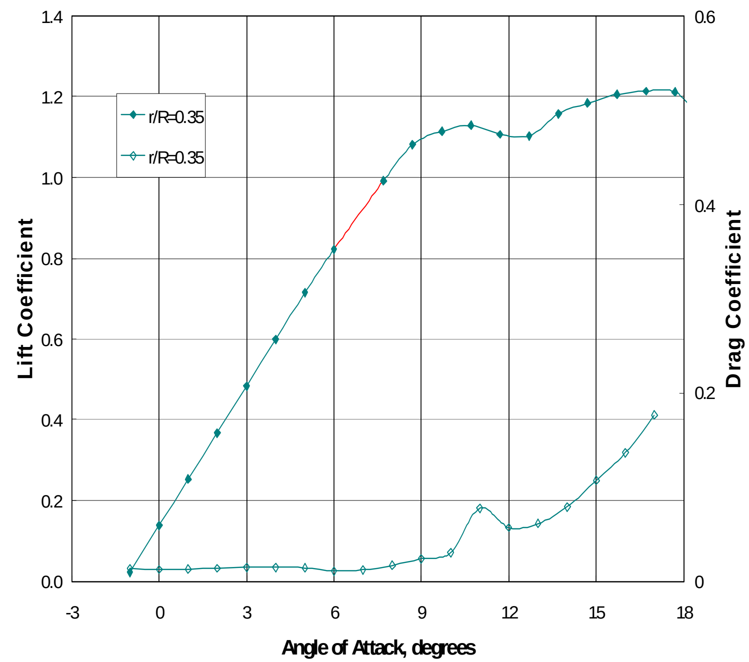
CER1 r/R	c/R	c/r	K	α Cl max	α Cl zero	$\Delta\alpha$	K*θ/0.136	$\Delta\alpha$ **(n=1)**
0.05	0.0911	1.822	0.1026	9	-1.2	10.2	1.3749	**3.8**
0.15	0.0911	0.607	0.2807	9	-1.2	10.2	1.2537	**2.6**
0.25	0.0911	0.364	0.4483	9	-1.2	10.2	1.2011	**2.1**
0.35	0.0911	0.260	0.6101	9	-1.2	10.2	1.1676	**1.7**
0.45	0.0911	0.202	0.7680	9	-1.2	10.2	1.1432	**1.5**
0.55	0.0911	0.166	0.9230	9	-1.2	10.2	1.1241	**1.3**
0.65	0.0911	0.140	1.0756	9	-1.2	10.2	1.1084	**1.1**
0.75	0.0911	0.121	1.2260	9	-1.2	10.2	1.0952	**1.0**
0.85	0.0911	0.107	1.3752	9	-1.2	10.2	1.0837	**0.9**
0.95	0.0911	0.096	1.5227	9	-1.2	10.2	1.0737	**0.8**

– CER3 tapered/twisted blade

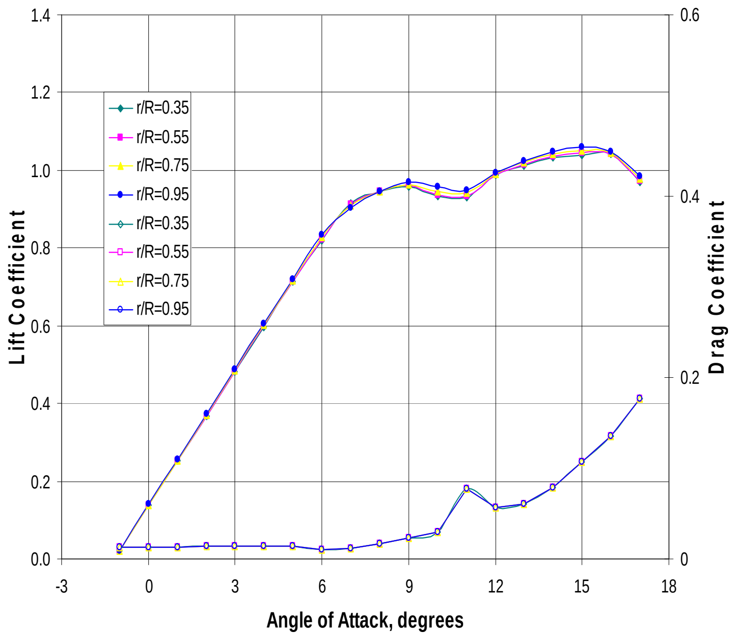
CER3 r/R	c/R	c/r	K	α Cl max	α Cl zero	$\Delta\alpha$	K*θ/0.136	**$\Delta\alpha$ (n=1)**
0.05	0.0442	0.886	0.1987	9	-1.2	10.2	1.2941	**3.0**
0.15	0.0510	0.341	0.4769	9	-1.2	10.2	1.1943	**2.0**
0.25	0.1465	0.586	0.2902	9	-1.2	10.2	1.2499	**2.5**
0.35	0.1364	0.390	0.4216	9	-1.2	10.2	1.2078	**2.1**
0.45	0.1263	0.281	0.5695	9	-1.2	10.2	1.1750	**1.8**
0.55	0.1162	0.211	0.7388	9	-1.2	10.2	1.1473	**1.5**
0.65	0.1061	0.163	0.9357	9	-1.2	10.2	1.1227	**1.3**
0.75	0.0960	0.128	1.1692	9	-1.2	10.2	1.1000	**1.0**
0.85	0.0859	0.101	1.4519	9	-1.2	10.2	1.0784	**0.8**
0.95	0.0758	0.080	1.8029	9	-1.2	10.2	1.0572	**0.6**

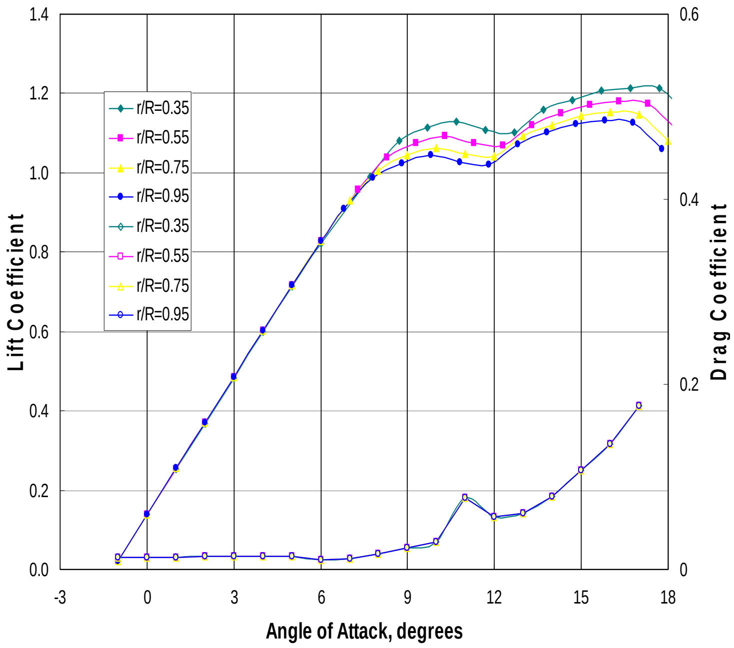
– S809 Delft 2-D data without/with stall delay



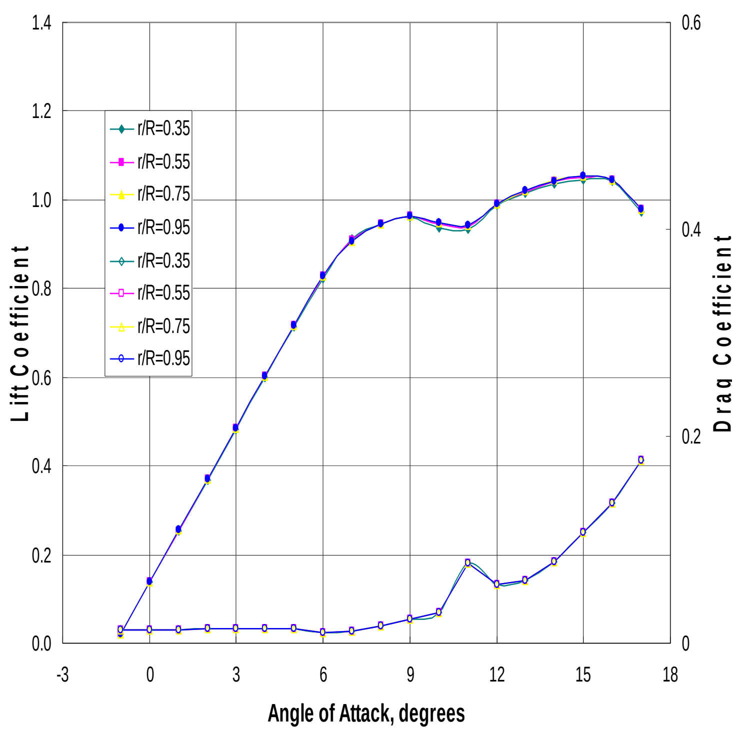


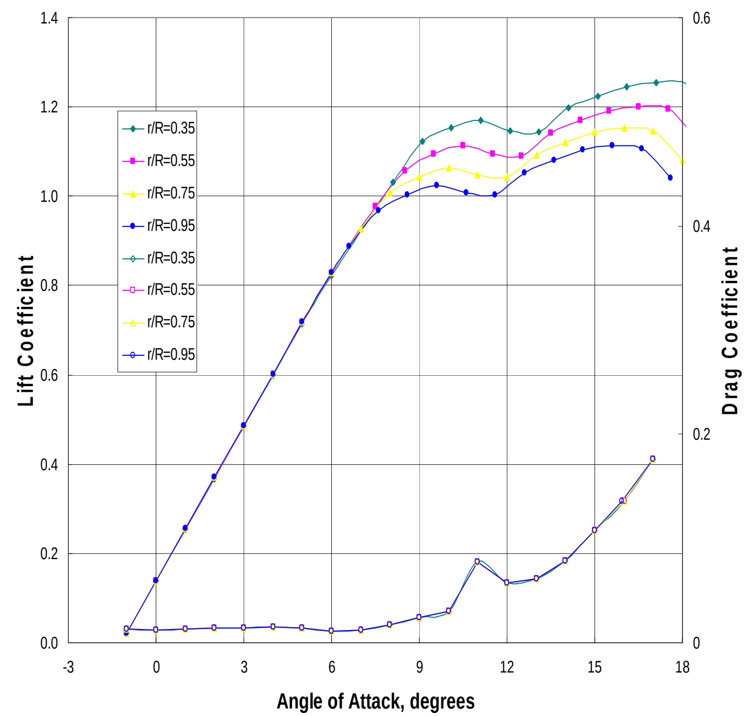
– CER1 airfoil data without/with stall delay



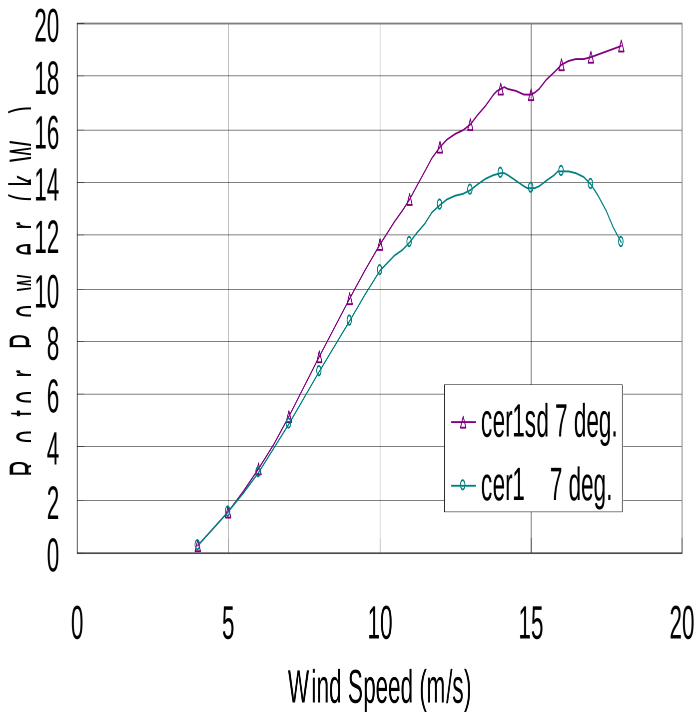


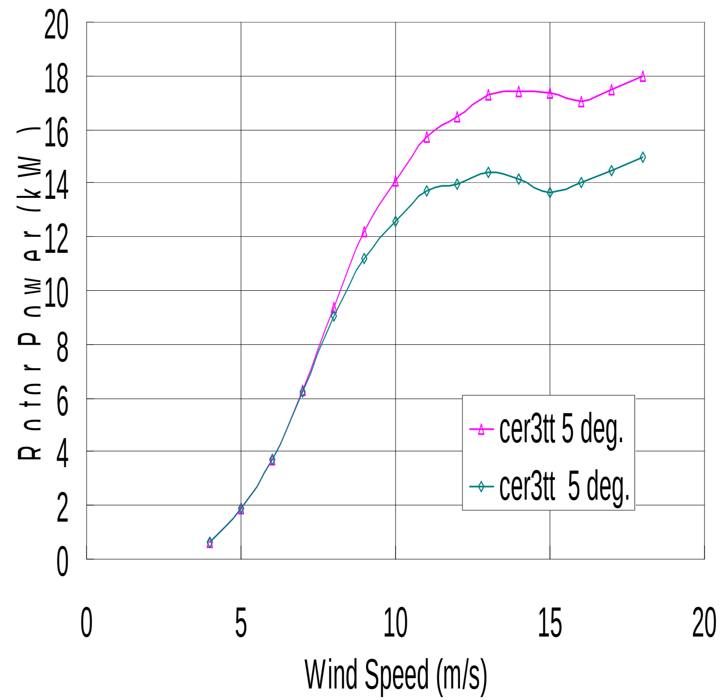
– CER3 airfoil data without/with stall delay





– CER1 and CER3 predicted power without/with stall delay





- UIUC Stall-Delay Model
  - Easier to tailor to CER test data than Corrigan & Schillings model
  - More rigorous analytical approach
  - Results in greater blade root lift coefficient enhancement than Corrigan & Schillings model

- Conclusions on Post-Stall Models
  - The Corrigan & Schillings stall delay model quantifies stall delay in terms of blade geometry
  - Greater blade solidity and airfoil camber resulted in greater stall delay
  - Tapered blade planform provided the same % peak power increase as constant-chord blade with lower blade loads
  - Predicted CER peak power with stall delay was 20% higher
  - Peak power increases of 10% to 15% are more realistic for lower solidity commercial machines