ECN

Energy research Centre of the Netherlands

Design of Thick Airfoils for Wind Turbines

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Introduction

Background

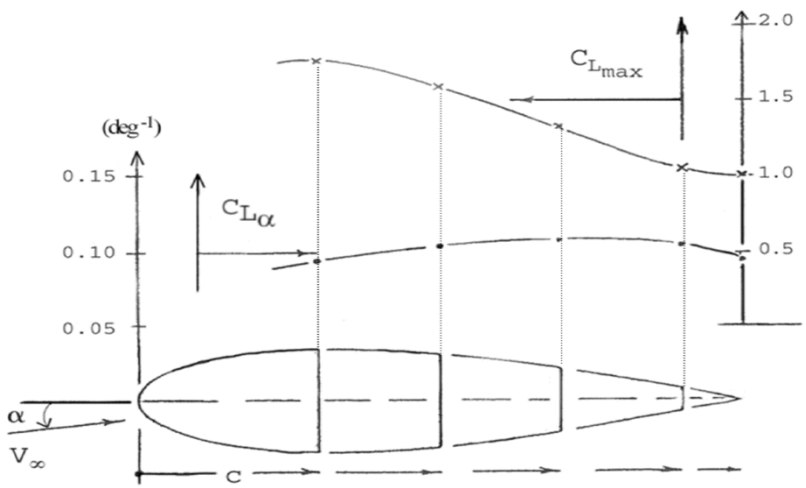
- *The choice of the airfoils is a crucial step in wind turbine design in order to obtain competitive performances.*
    - ***NREL airfoils (Somers and Tangler)***
    - ***FFA airfoil family (Bjork)***
    - ***Stuttgart airfoils (Althaus, Wortmann)***
    - ***DU airfoils (Timmer et al.)***
    - ***Risoe airfoil families***
    - ***In house developed airfoils (Companies….)***
- *Most of the airfoils available in literature are designed for the outer part of the blade (15%-25% relative thickness).*

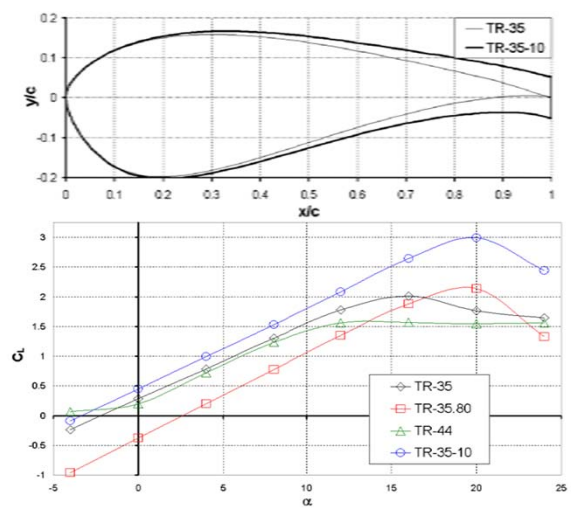
Thick Airfoils for Wind Turbines

State of the art

- *Beside the aerodynamic performance, the airfoils for inner part of the blade have to guarantee the structural resistance of the blade.*

- *Research in this area are focused on exploring new solutions to accomplish both aerodynamic and structural performance (i.e. flatback airfoils improve both lift performance and structure[1,2]).*





1. Hoerner, S. F., and Borst, H. V., *Fluid-Dynamic Lift*, Hoerner Fluid Dynamics, Bricktown, NJ, 1985, pp. 2-10, 2-11
2. van Dam, C.P., Mayda, E.A., and Chao, D.D., "Computational Design and Analysis of Flatback Airfoil Wind Tunnel Experiments", SAND2008-1782, Sandia National Laboratories, Albuquerque, NM, March 2008

Thick Airfoils for Wind Turbines

Requirements

- ***Structure***
  - *High structural strength*
  - *Not too strong blade torsion*
- ***Aerodynamics***
  - *High aerodynamic efficiency (L/D)*
  - *Good performance in off-design conditions*
  - *Insensitivity to the roughness*
  - *Good stall characteristics*
  - *Margin between design condition and stall (gust robustness)*
- ***Geometry***
  - *Sufficient internal space for the spar*
  - *Compatibility with the other airfoils along the blade*

Inboard sections are usually working at high assets.
Smooth stall behavior and margin before stall for gust can be desiderable features

Design Approach

Design Approach

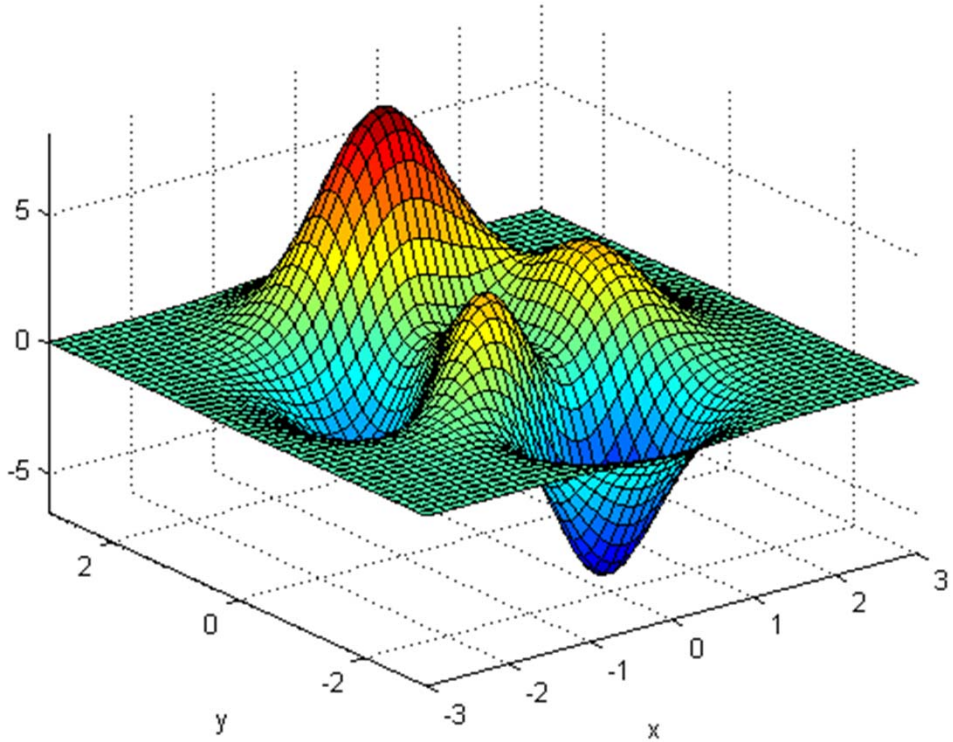
Numerical optimization - the general formulation

Minimize/Maximize : $F(X)$

Subject to: $\begin{cases} g_j(X) \le 0 & j = 1, M \\ h_k(X) = 0 & k = 1, L \end{cases}$

By modifying:

$$X_i^L \le X_i \le X_i^U \quad i = 1, N$$



Design Approach

Numerical optimization - hybrid scheme:

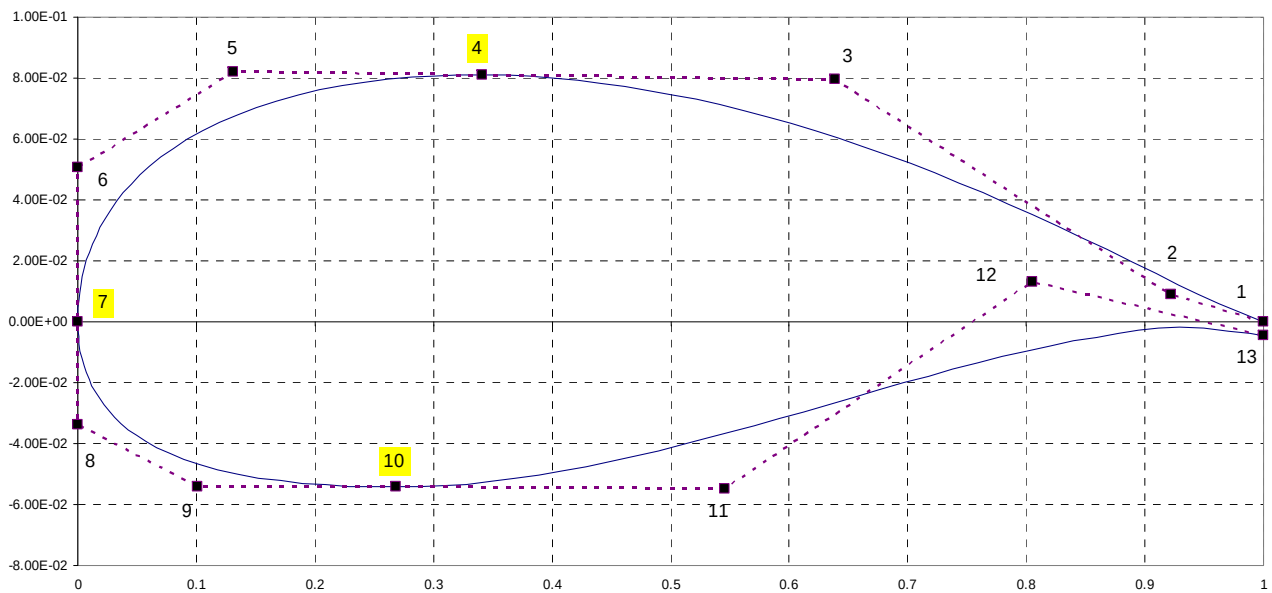
- *Genetic Algorithms (**GA**) are less sensitive to local optima and able to explore wide domains, but computationally expensive.*
- *Gradient Based Algorithms (**GBA**) are usually more accurate than **GA** but also more sensitive to the initial condition and to local optima.*
- *A combination of **GA** and **GBA** can improve the accuracy and robustness of the optimal solution.*

Design Approach

Geometry parameterization:

- *The airfoil is divided in 4 parts. Each part is described by a cubic Bezier curve.*

$$P(t) = P_0(1-t)^3 + 3P_1 t(1-t)^2 + 3P_2 t^2(1-t) + P_3 t^3 \qquad t \in (0,1)$$



13 control points

⇩

26 (theoretical) d.o.f.

- *L.E. fixed **(-2)***
- *T.E. moves only in vertical **(-3*)***
- *Control points 4 and 10 internally controlled **(-4)***
- *For subsonic airfoils, control points 6 and 8 move only in vertical **(-2)***

⇩

15 active d.o.f.

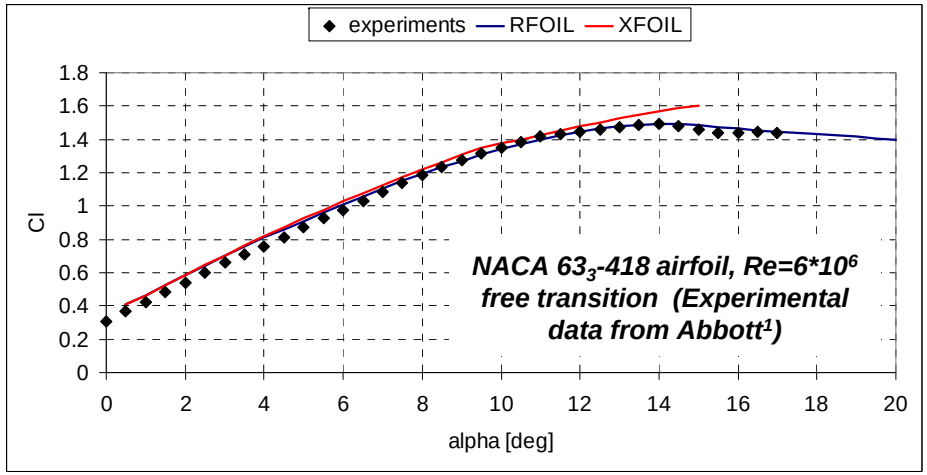
Design Approach

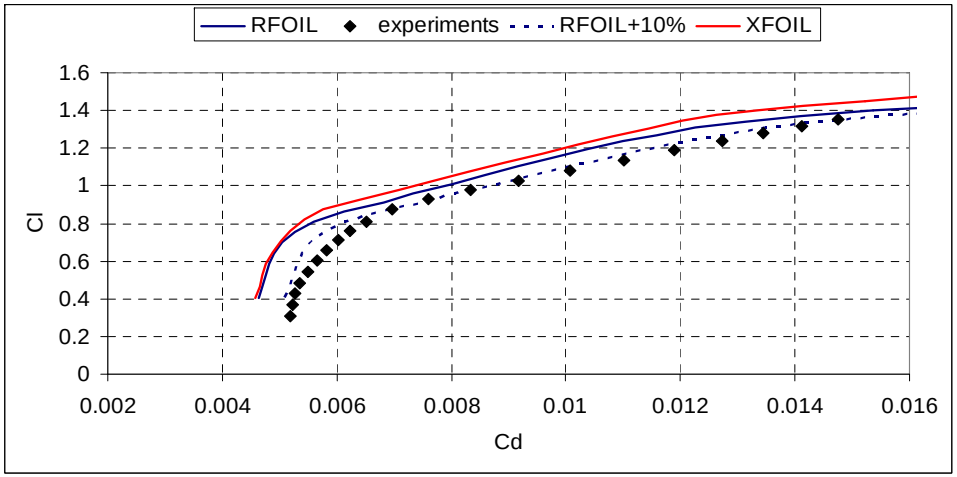
Objective function definition and evaluation:

$$F = (1-k)W + k(L/D) \qquad t \in (0,1)$$

RFOIL

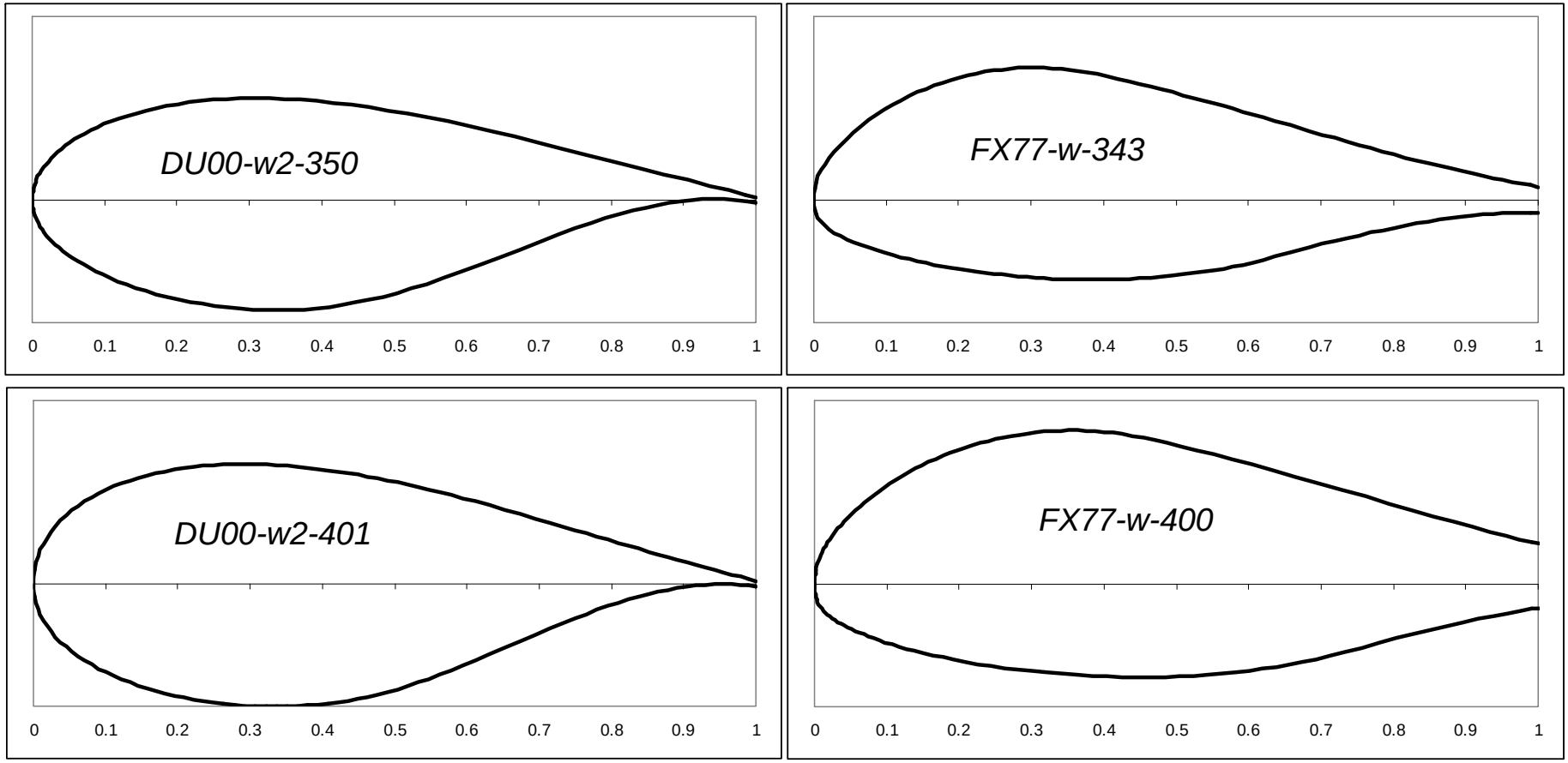
- *Improvements in boundary layer description*
- *Effects due to the rotation taken into account*





1. Abbott, I., Von Doenhoff, A., *Theory of Wing Sections*, Dover Publications, Inc., Dover edition, 1958

Validation of RFOIL for thick airfoils:



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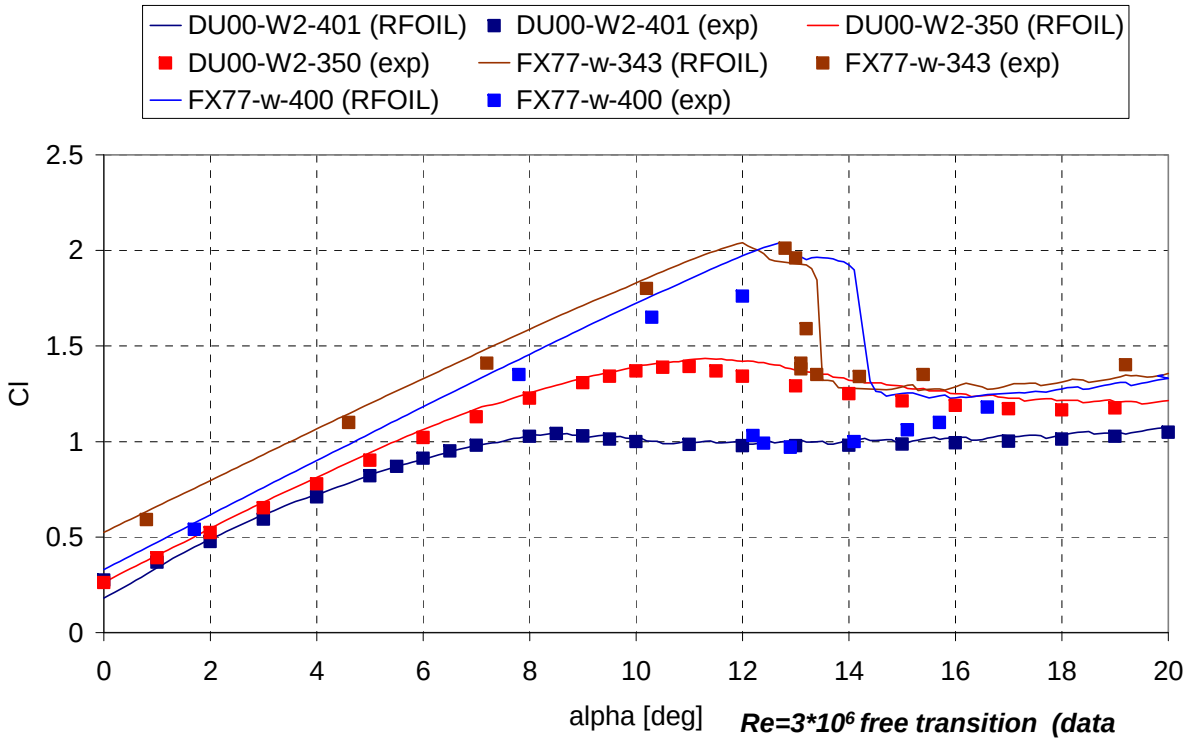
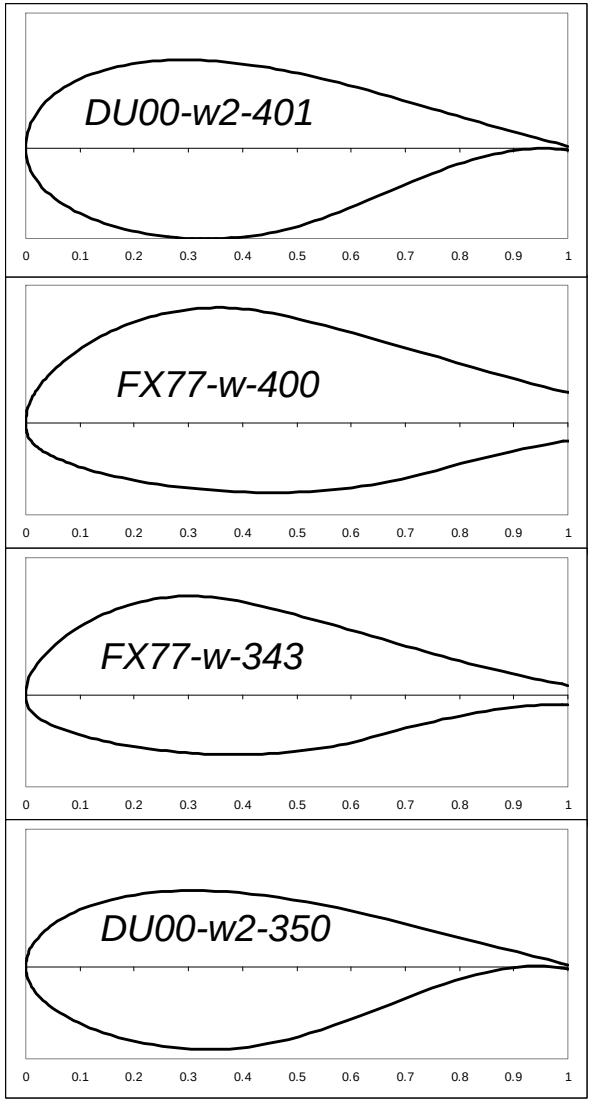


Re=3*10⁶ free transition (data from Delft and Stuttgart universities)



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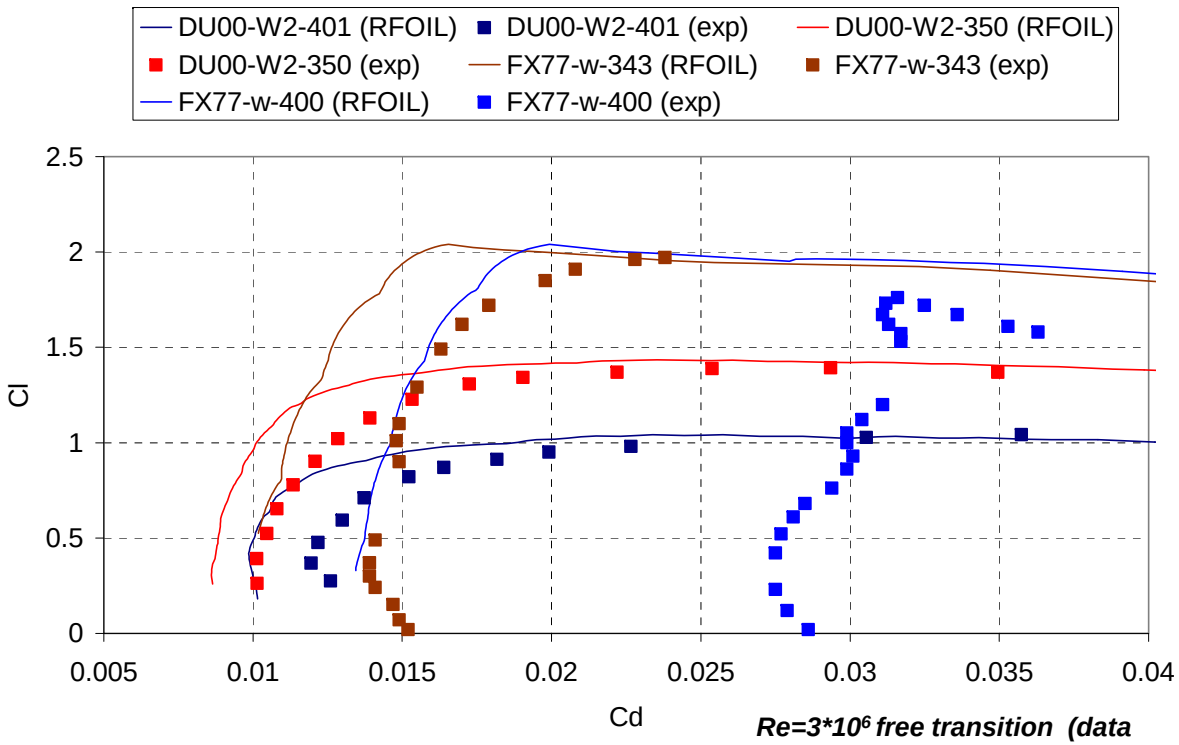
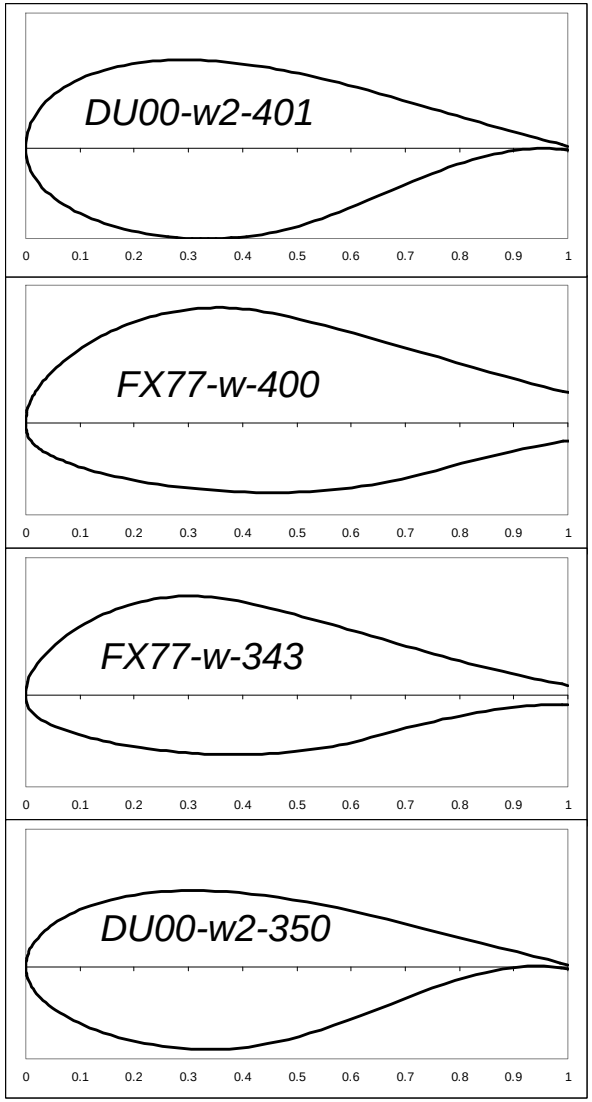


Re=3*10^6 free transition (data from Delft and Stuttgart universities)



Hybrid Scheme: preliminary tests

Hybrid Scheme: preliminary tests

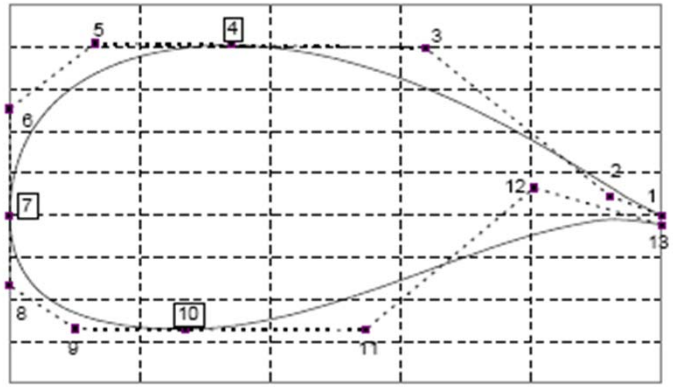
Definition of the problem: general settings

- ***Objective function***
  - *Maximize L/D @ 6deg*
- ***Design conditions***
  - *Re: 3 million*
  - *Fixed transition: 1% on suction side, 10% on pressure side*
- ***Constraints***
  - *Airfoil thickness > 35%c*
  - *Trailing edge thickness > 1%c*
  - *$Cm_{c/4}$@ 6deg > -0.15*

Hybrid Scheme: preliminary tests

Definition of the problem: degrees of freedom

ID	Control point*	Lower bound (%chord)	Upper bound (%chord)
1	2h	0.7	0.8
2	3h	0.4	0.5
3	5h	0.09	0.15
4	9h	0.09	0.15
5	11h	0.4	0.5
6	12h	0.7	0.8
7	1v	0	0.1
8	2v	0.03	0.2
9	3v	0.08	0.25
10	5v	0.08	0.25
11	6v	0.03	0.1
12	8v	-0.1	-0.02
13	9v	-0.25	-0.02
14	11v	-0.25	0.04
15	12v	-0.1	0.09
* h denotes horizontal direction, v denotes vertical direction. Numbers refer to figure 1			



TE thickness can change up to 20%c

Airfoil thickness can change between 10%c and 50%c

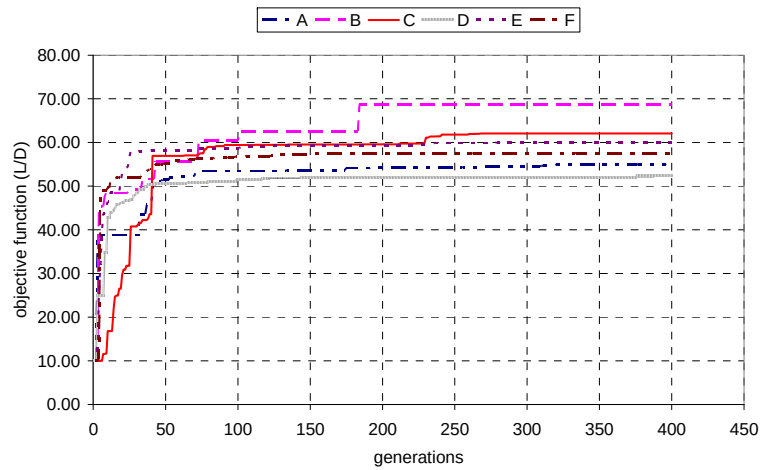
Hybrid Scheme: preliminary tests

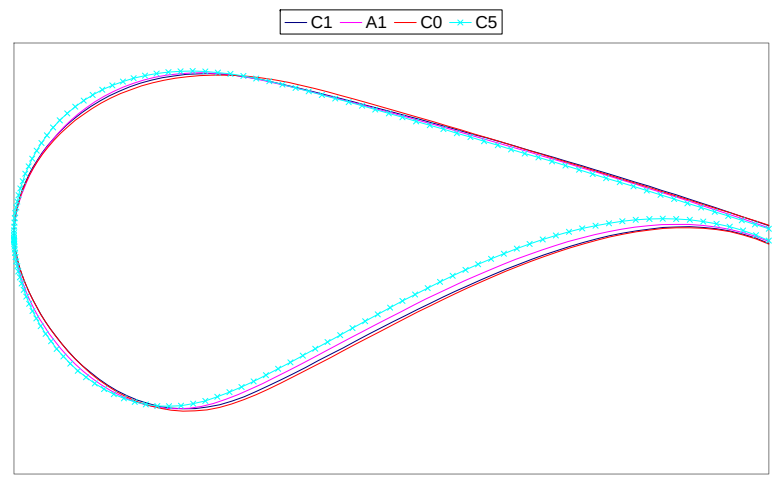
Results

ID	microGA	population	children	Time (min)	L/D
A	yes	5	1	25	55.48
B	yes	10	1	130	68
C	no	5	1	43	62.1
D	no	5	2	30	52.4
E	no	10	1	150	60
F	no	10	2	70	57.7

ID	microGA	population	children	Time (min)	L/D
A	yes	5	1	110	55.7
B	yes	10	1	130	55.7
C	no	5	1	170	56
D	no	5	2	120	53

ID	GA generation	L/D			T (sec)
		GA	GBA	Δ%	
A1	400	55.48	60	8.14708	453
C0	4	10	58	480	652
C1	25	31.7	60	89.27445	767
C2	50	56.9	56.9	0	935
C3	100	59.4	59.42	0.03367	125
C4	200	59.6	59.62	0.033557	128
C5	400	62	62.05	0.080645	121





Design of New Thick Airfoils

Design of New Thick Airfoils

Definition of the problem: design requirements

- ***Structure***
  1. *High structural strength*
  2. *Not too strong blade torsion*
- ***Aerodynamics***
  3. *High aerodynamic efficiency (L/D)*
  4. *Good performance in off-design conditions*
  5. *Insensitivity to the roughness*
  6. *Good stall characteristics*
  7. *Margin between design condition and stall (gust robustness)*
- ***Geometry***
  8. *Sufficient internal space for the spar*
  9. *Compatibility with the other airfoils along the blade*

- ***Objective function***
  - *Maximize moment of resistance **(1)***
  - *Maximize L/D @ 6deg **(3)***
  - *Aerodynamics and structure are mixed together by weighted linear combination*
- ***Design conditions***
  - *Re: 3 million*
  - *Fixed transition: 1% on suction side, 10% on pressure side **(4, 5)***
- ***Constraints***
  - *Airfoil thickness > 35%c **(8, 9)***
  - *Trailing edge thickness > 1%c **(9)***
  - *$Cm_{c/4}$@ 6deg > -0.15 **(2,9)***
  - *Cl drop @15-16deg <-0.3 **(6, 7)***

Design of New Thick Airfoils

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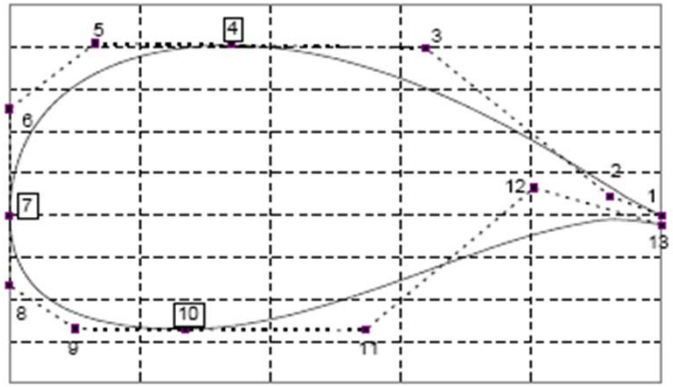
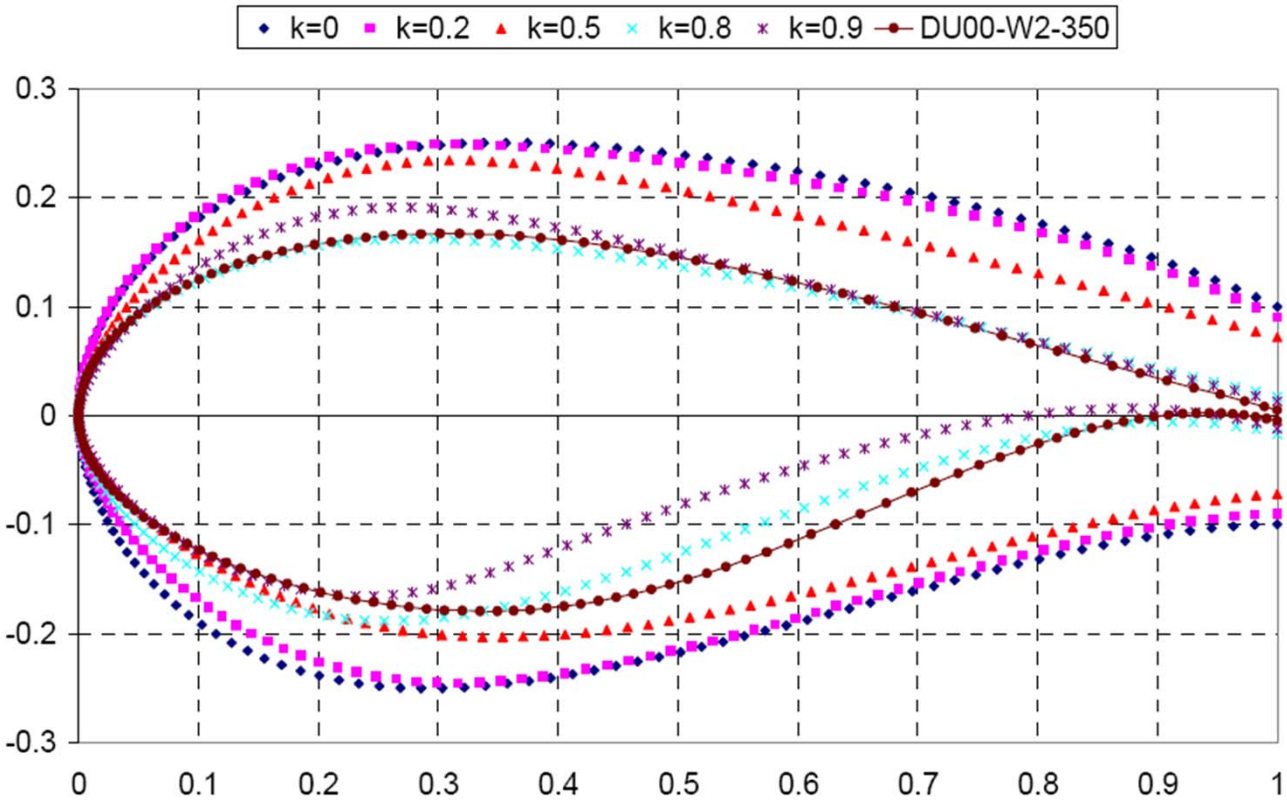


TE thickness can change up to 20%c

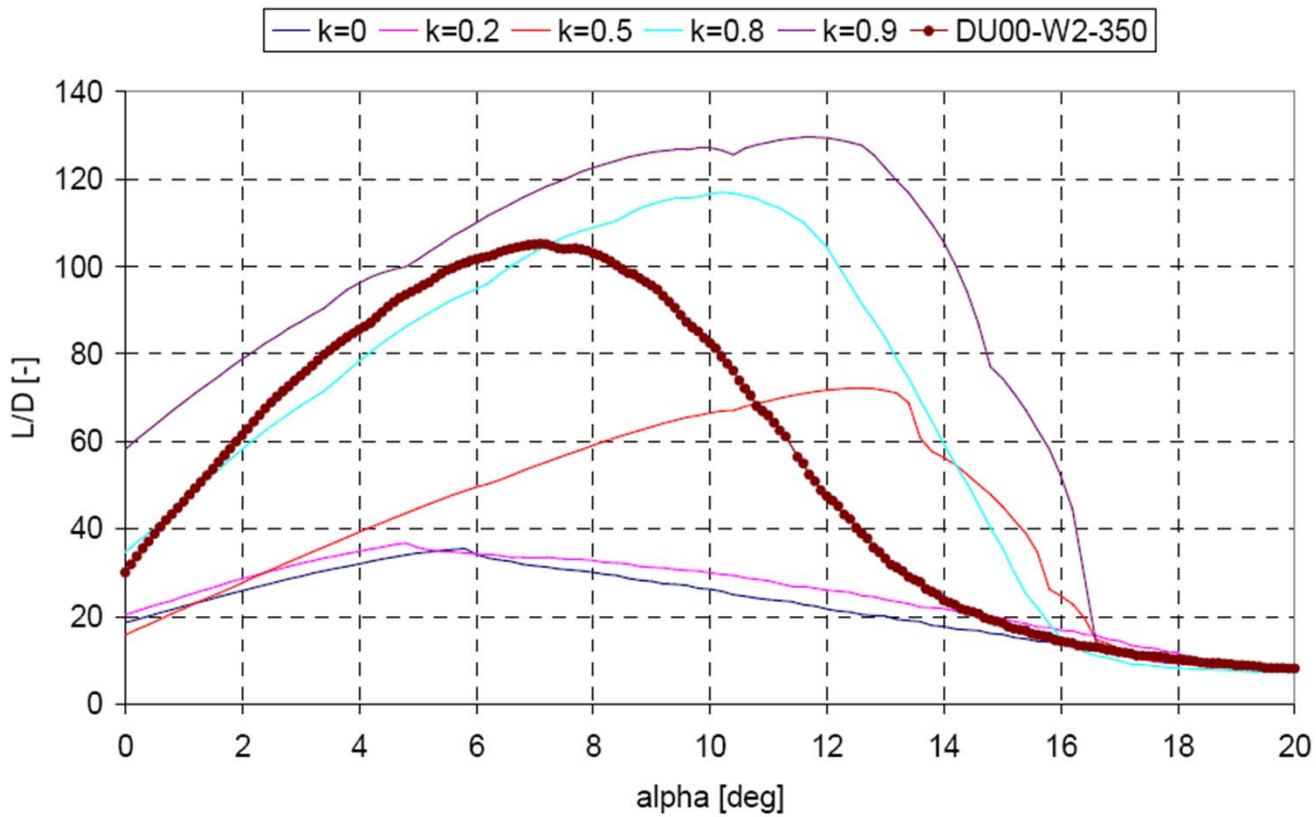
Airfoil thickness can change between 10%c and 50%c

Results: geometries



- *Family of thick airfoils*
- *Feasible shapes, consistent with the requirements*
- *Thickness ranging between 35% (priority to the aerodynamics) to the 50% (priority to the structure)*
- *The thicker geometries exhibit flatback TE*

Results: aerodynamic efficiency *(RFOIL predictions, Re 3million, free transition)*

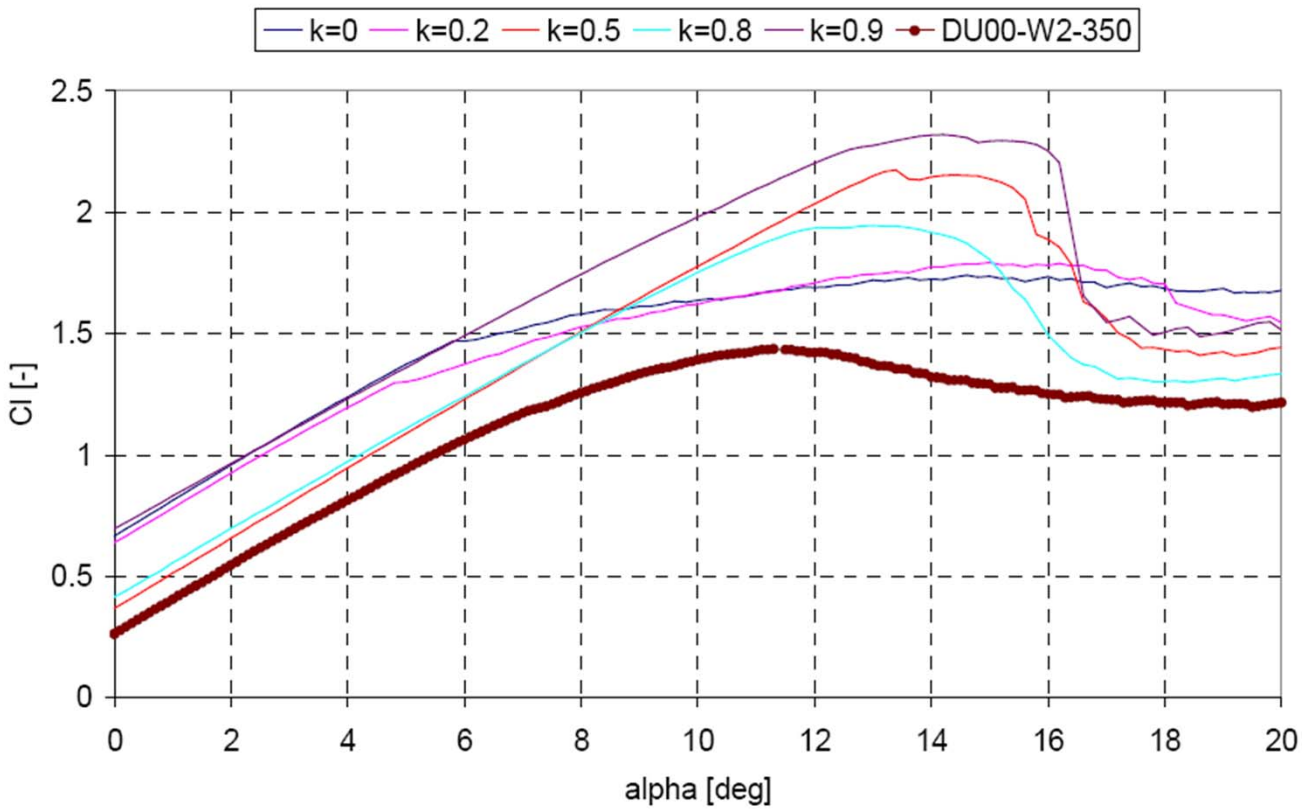


w.r.t k0.8 and k0.9 airfoils

- *Good L/D_{max} value, higher than DU00-w2-350 airfoil*
- *Good general performance, also in off design conditions*

Design of New Thick Airfoils

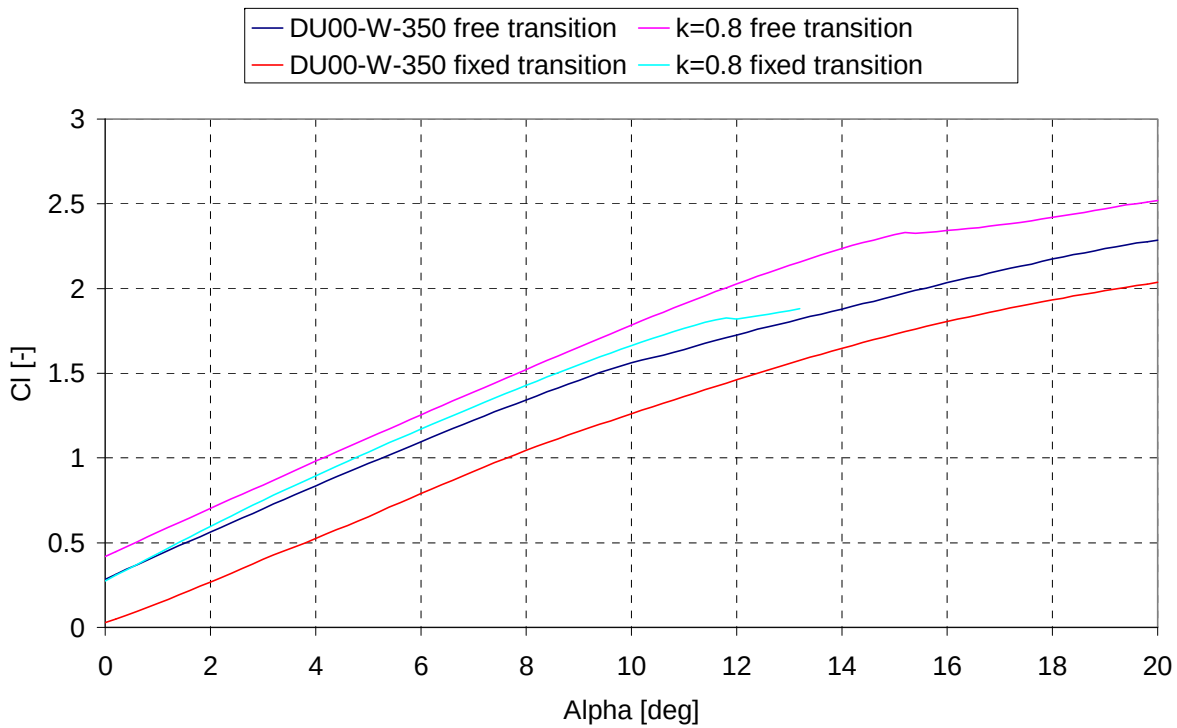
Results: lift coefficient *(RFOIL predictions, Re 3million, free transition)*



w.r.t k0.8 and k0.9 airfoils

- *Good value of Cl_{max}*
- *Good extension of the linear part of the curve*
- *K0.8 airfoil exhibits quite smooth stall*
- *Good margin before stall*
- *Better Cl performance. w.r.t. DU00-w2-350 can lead to chord and mass reduction*

Results: rotational effects[1] *(RFOIL predictions, Re 3million, free and fixed transition)*



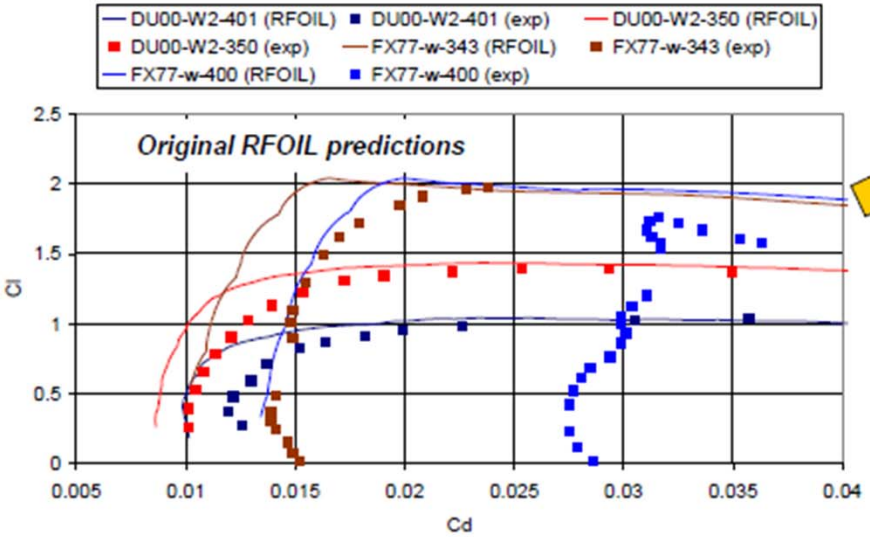
- *Better lift performance both in free and fixed transition*

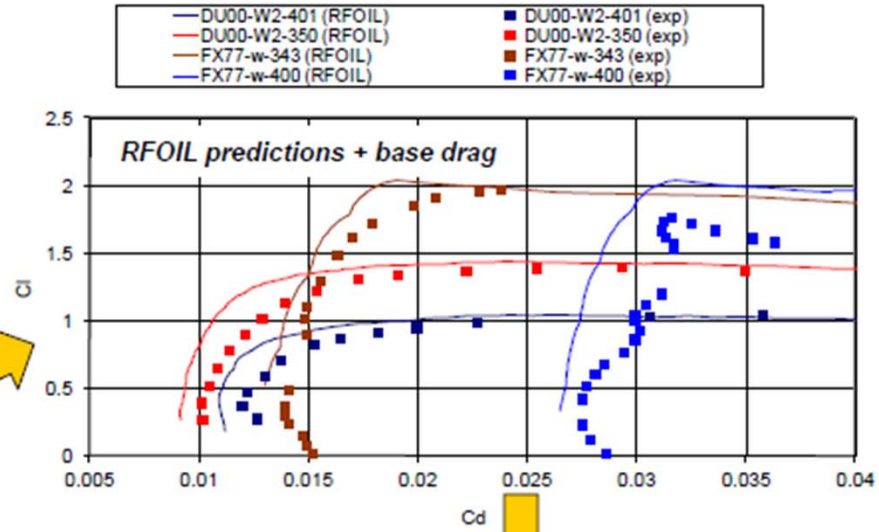
1. Snel, H., Houwink, R., van Bussel, G.J.W., Bruining, A., 'Sectional Prediction of 3D Effects for Stalled Flow on Rotating Blades and Comparison with Measurements', Proc. European Community Wind Energy Conference, Lübeck-Travemünde, Germany, 8-12 March, 1993, pp. 395-399, H.S. Stephens & Associates

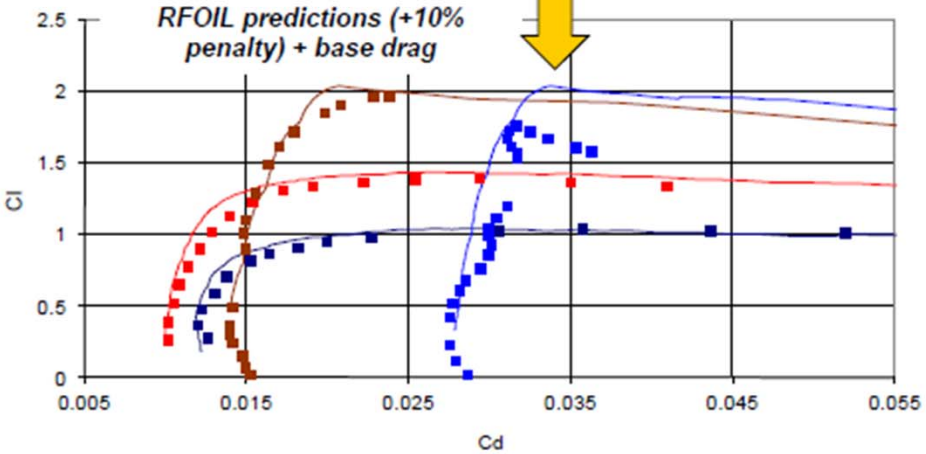
The Role of the Base Drag

The Role of the Base Drag

Base drag contribution:



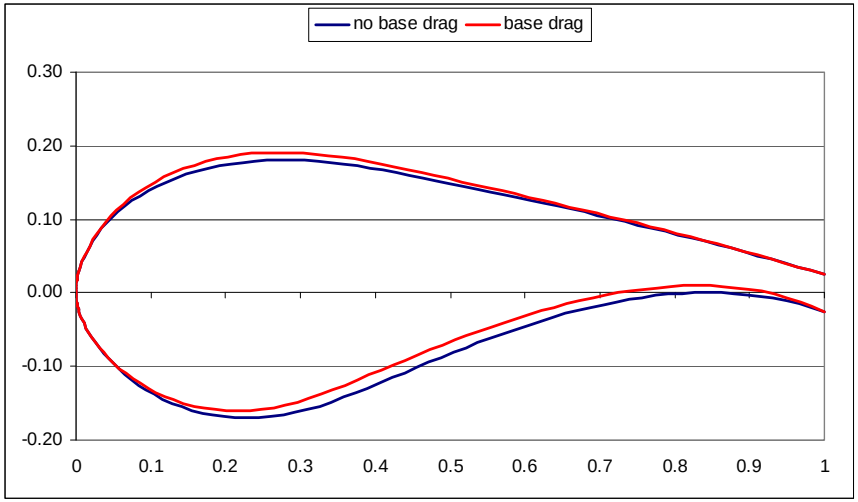


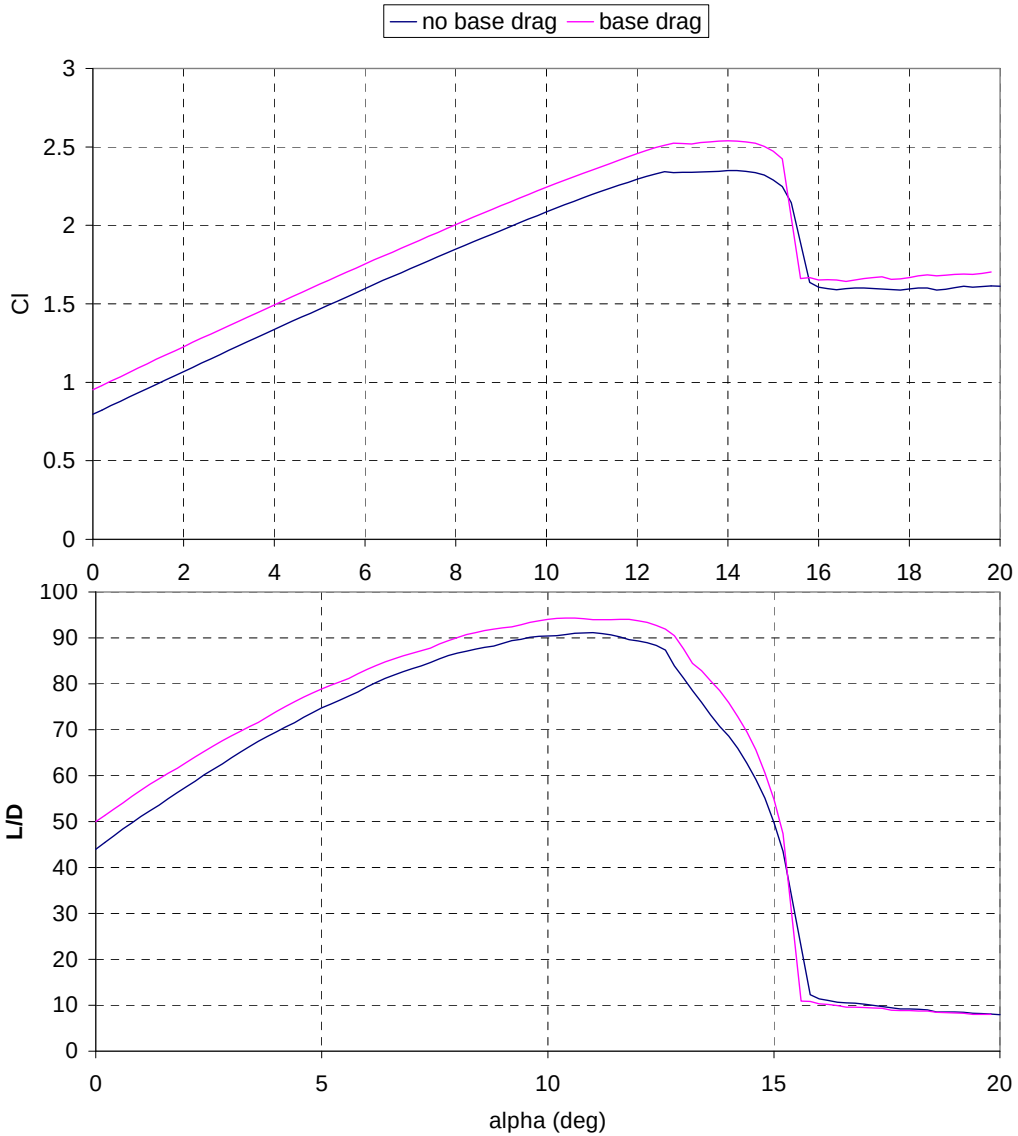


$$Cd_{base} = f(\mathrm{Re}, Cd, t, t_{TE})$$

The Role of the Base Drag

Effects on the airfoil:





Conclusions & Remarks

- *A hybrid optimization scheme making use of genetic algorithms and gradient based algorithms has been developed. The preliminary results are promising*

- *The results showed that this approach improves the accuracy and the robustness of the design.*

- *The base drag plays an important role on the performance of thick airfoils. A semi-empirical model is in development at ECN*

- *Wind tunnel tests are anyway necessary to validate numerical results.*