Airfoil Design for Hydrogen Aircraft

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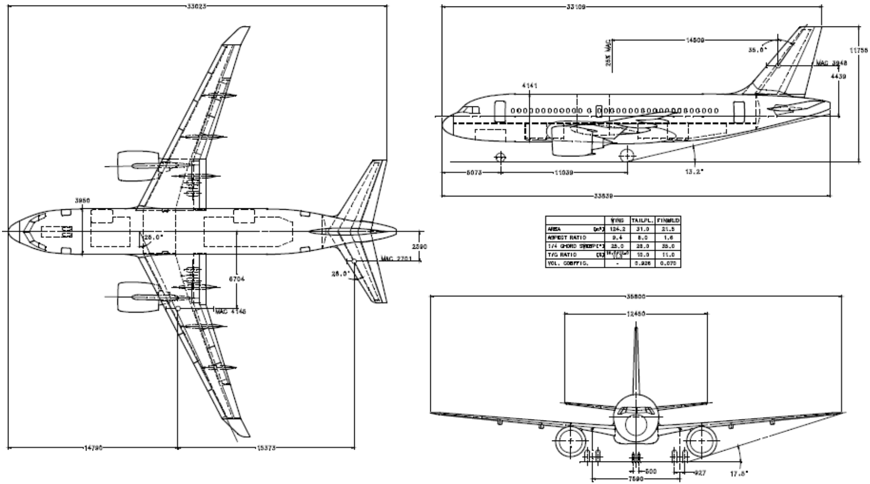
Introduction

- **Hydrogen Aircraft Commercial Aircraft**
- **Improve Aerodynamic Efficiency**
- **Mid-wing analysis**

	Top Level Aircraft Requirements (TLAR)
SPP payload	150 Passengers in single class seating (29" seat pitch) 95 kg per Passenger (incl. luggage) > total standard payload of 14250 kg
MTOM	70000 kg
Range	1500 nm with SPP (800 nm for economical evaluation)
TOFL	$\leq$ 2000 m (ISA, 15°C, MSL, MTOM)
ICAC	Optimum SAR altitude (after take-off @ MTOM)
Cruise Speed	$\geq$ Ma 0.65
Approach speed	$\leq$140 kts (sea level ISA, 15°C, @MLW)
Wing Span	36 m at gate (ICAC Annex 14 Code C)

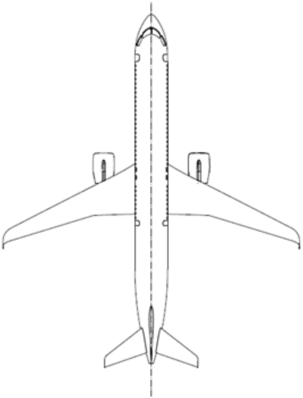
Reference Aircraft - A319Neo

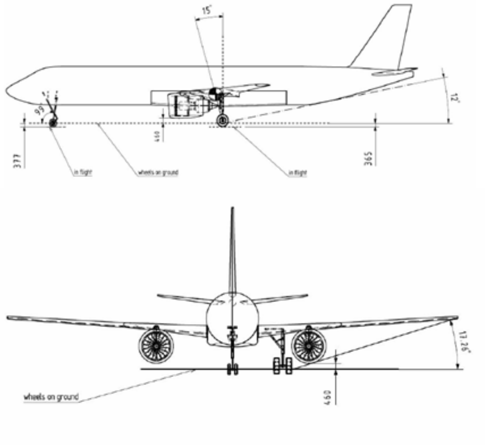


	WING	TAILPL.	FINBLD
AREA (m²)	124.2	31.0	21.5
ASPECT RATIO	9.4	5.0	1.6
1/4 CHORD SWEEP (°)	25.0	28.0	35.0
T/C RATIO (%)	[illegible]	10.0	11.0
VOL. COEFFIC.	-	0.926	0.070

Source: Airbus. Aircraft design towards carbon free air travel. Aircraft Design Seminar

Designed Aircraft - HCraft

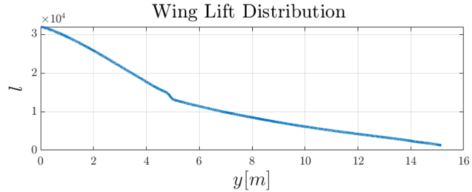


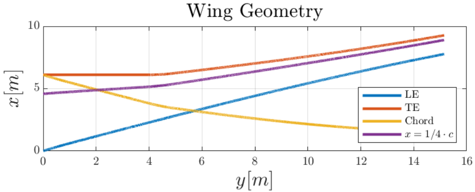


Wing Geometry

Main Wing Parameters	
Geometry	
Wingspan b [m]	36
Wing Area S_w $[m^2]$	124.5
Aspect Ratio Λ_W	10.41
Incidence Angle i_W [°]	3.5
Dihedral Γ [°]	5
Sweep Λ [°]	23.33
Section 1	
Airfoil	Airbus TA11
Twist	-0.5
Root Chord c_{root} $[m]$	6.094
Tip Chord c_{tip} $[m]$	3.564
Tapper Ratio λ_1	0.5848
Section 2	
Airfoil	Airbus TA11
Root Chord c_{root} $[m]$	3.564
Tip Chord c_{tip} $[m]$	1.5
Twist [°]	-3
Tapper Ratio λ_2	0.4208

$$M_c = 0.65$$
$$h_c = 11 \quad km$$
$$V_\infty = 193.93 \quad m/s$$
$$\rho = 0.37 \quad kg/m^3$$
$$c_{mean} = 3.0484 \quad m$$



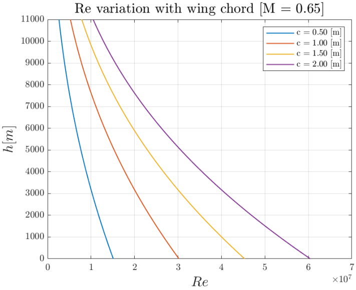


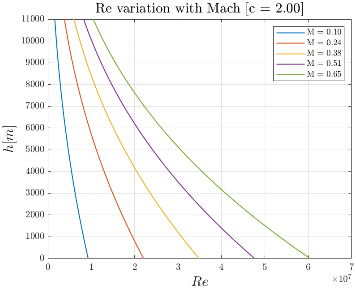
$$c_l = \frac{MTOW}{0.5\rho v_\infty^2 \cdot S_W} \cdot \frac{0.9}{0.9} \approx 0.79$$

The red number accounts to the lift generated by fuselage and the green for the AF lift estimation.

Airfoil Requirements

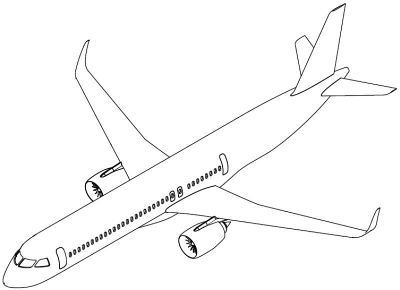
Stage: Cruise
Chord c: 2 $[m]$
Airfoil c_l**:** 0.79
Angle of attack α [°]: [-4, 10]
Relative thickness t**:** $[10, 14]\%$
Reynolds number Re**:** $Re \approx 1 \cdot 10^7$





The selected analysis parameters have been chosen in order to be able to analyze the non-compressible behaviour.

- **Design Objectives**
  - Reduced Airfoil Thickness
  - Drag Reduction
  - Reduce fuel consumption
  - Improve Stall Behaviour



The airfoil minimum thickness is to be estimated based on the drag minimization criteria.
The rear fuselage integrated LH2 tanks leaves the option of reducing the AF thickness.

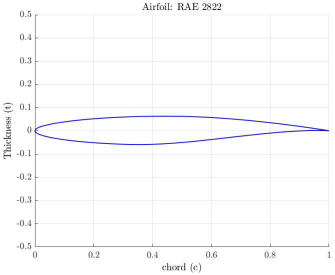
Design Parameters

Because of the wing sweep the incidence velocity is not the same as the freestream.
The following correction has to be applied:

$$M_{c,eff} = M_c \cdot cos(\Lambda) = 0.65 \cdot cos(23.33) \approx 0.6$$

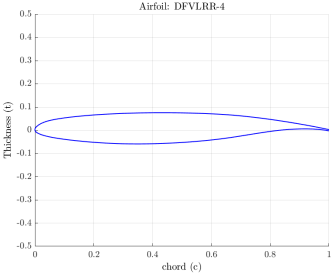
$$Re = 7 \cdot 10^6$$

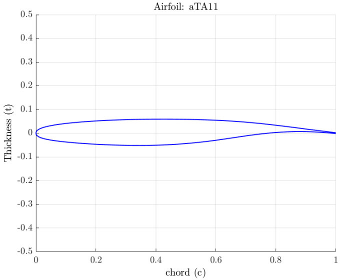
Reference Airfoils

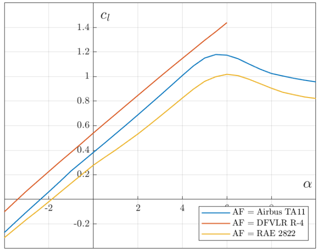


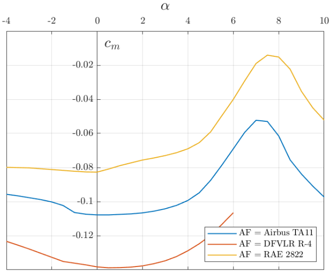
Supercritical Airfoil
- Shock wave delay
- Reduce shock drag - Higher cruise M
- Market acceptance

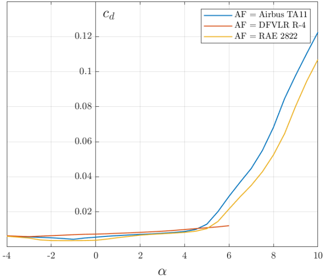
	Thickness (t)	Max. t position	Max. camber	Max. camber position
DFVLR R-4	13.38%	37.94%	2.1%	80.48%
Airbus TA11	11.04%	37.54%	1.86%	76.78%
RAE 2822	12.11%	37.84%	1.26%	15.68%







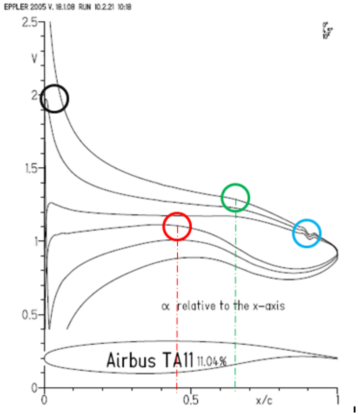




Airbus TA11

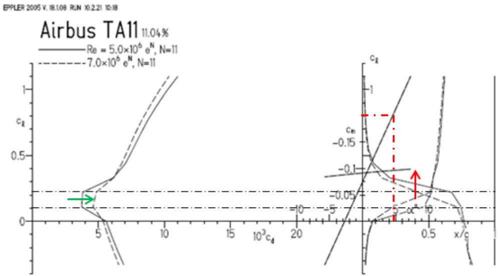
- Wider non-compressible range
- Compromise among other options
- Smallest thickness
- Keep aerodynamic properties at low speed

Airbus TA11



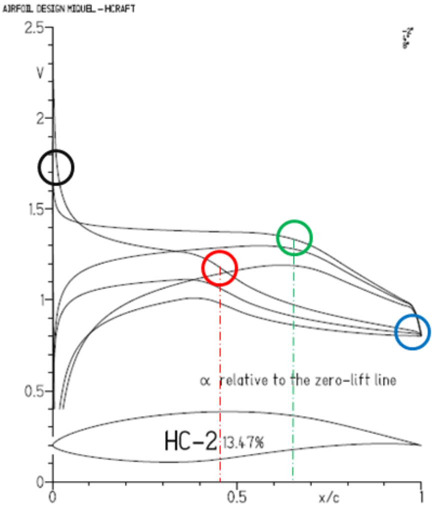
Observations:

- Strong HDA on the lower side
- **Suction peak** on the upper side close to the LE
- Irregular velocity instability close to the TE
- No lower side separation
- LS_t $x/t \approx 0.45$ - US_t $x/t \approx 0.65$



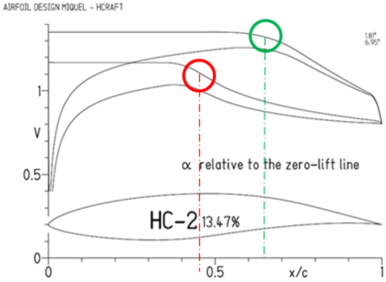
$c_l = 0.8$ for an $\alpha \approx 5^\circ$

Design Process

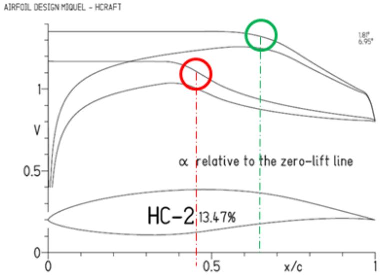


Parameters:

$v_1^* = 0, \quad \alpha_{US}^* = 7.27, \quad c_l = 0.8$
$v_1^* = 60, \quad \alpha_{LS}^* = 1.818, \quad c_l = 0.2$
$\Delta v_{f,US} = 3, \quad \Delta v_{r,US} = 2$
$\Delta v_{f,LS} = 1.5, \quad \Delta v_{r,LS} = 1$
$x/t_{US} \approx 0.65, \quad x/t_{LS} \approx 0.5$
$\lambda^* = 3, \quad \lambda = 12, \quad RSM = 2, \quad \mu = -1, \omega = 0.7$
$\overline{\lambda^*} = 2.5, \quad \overline{\lambda} = 15, \quad \overline{RSM} = 2, \quad \overline{\mu} = 0.23, \overline{\omega} = 0.7$

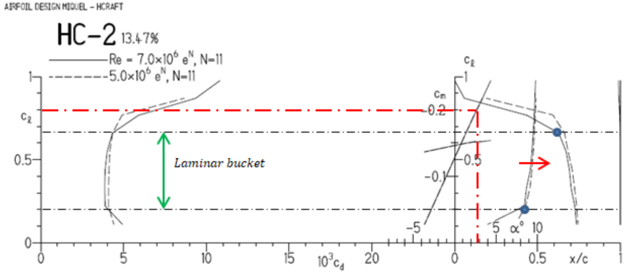


Intermediate Design

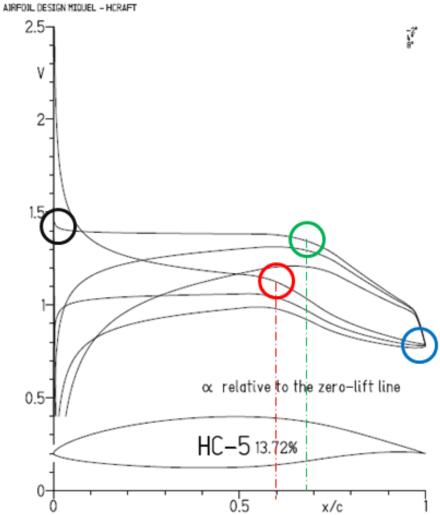


Observations:

- Bigger laminar bucket expected
- Improved transition for US-LE
- Transition for LS-LE to be improved
- Good separation for LS and US TE
- $c_l = 0.8$ for an $\alpha \approx 3^\circ$
- Improved c_m
- Drag reduced



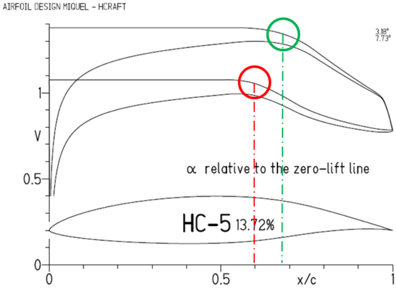
Final Design

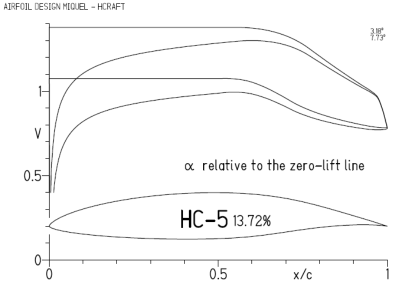


Parameters:

$v_1^* = 0, \quad \alpha_{US}^* = 8.18, \quad c_l = 0.9$
$v_1^* = 60, \quad \alpha_{LS}^* = 3.18, \quad c_l = 0.35$
$\Delta v_{f,US} = 3, \quad \Delta v_{r,US} = 2$
$\Delta v_{f,LS} = 2, \quad \Delta v_{r,LS} = 1.5$ Softer transition
$x/t_{US} \approx 0.68, \quad x/t_{LS} \approx 0.7$
$\lambda^* = 3.5, \quad \lambda = 11.5, \quad RSM = 2, \quad \mu = -1, \omega = 0.685$
$\overline{\lambda^*} = 3.5, \quad \overline{\lambda} = 11, \quad \overline{RSM} = 2, \quad \overline{\mu} = 0.23, \overline{\omega} = 0.72$

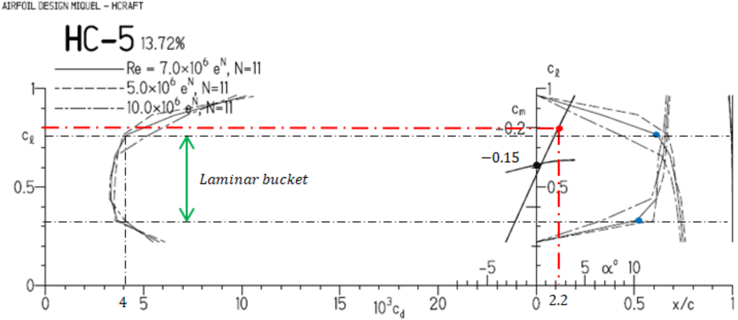
- Softer US-LE **suction peak** for high α



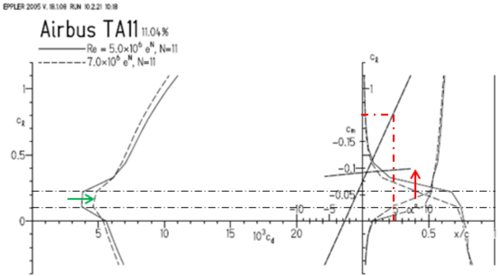


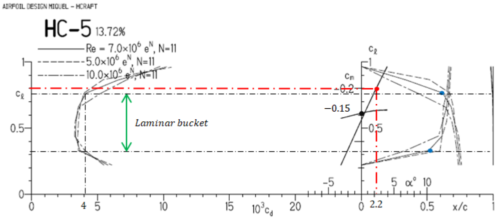
Observations:

- Adjusted laminar bucket
- Improved transition for LS-LE
- Good separation for LS and US TE
- $c_l = 0.8$ for an $\alpha \approx 2.2°$
- Targeted c_l close to the optimal one
- Reasonable c_m
- Drag increase for $Re = 10 \cdot 10^6$
- No TE separation for both sides
- Slightly increased t



Comparison





Comments:

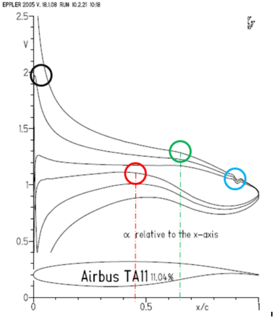
- Better lift distribution over US & LS
- Transition shifted to the TE
- Adjusted optimized laminar bucket
- Greater **lift** with lower **drag**
- Optimal c_m not too high, not too low

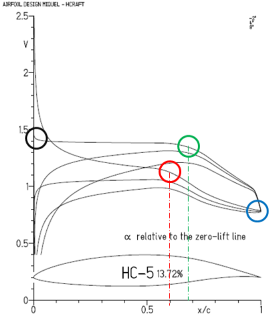
Reynolds:

- Considered possible flight Re to study behaviour
- Increase Re results in a laminar bucket reduction
- Lower Re shows always a better behaviour

Conclusions

- Stall not reached for cruise but a further analysis is needed
- Increased thickness from ATA11 AF but with lower drag
- The possibility of improving the AF for higher Re should be considered
- A better analysis for reference AF should be performed with the Eppler code
- A further analysis for non cruise flight regimes should be done

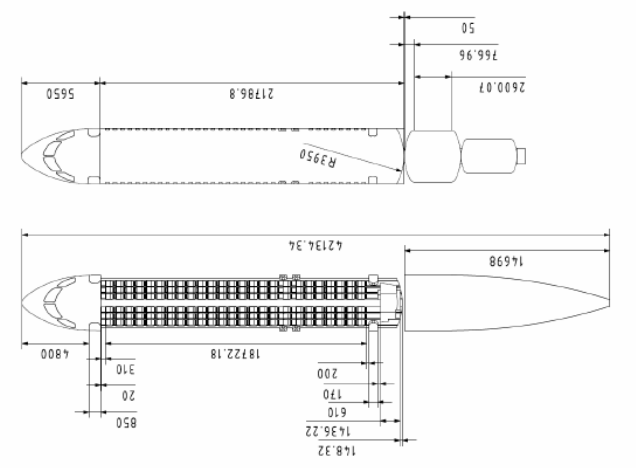




- Substantial improvement from ATA11 AF
- Still a big improvement gap for the HC-5 AF
- The Eppler code gave a better undertanding on how the AF velocity profile affects its properties

Questions?

Backup



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310
20
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200
170
610
1436.22
148.32

Backup