

Università degli Studi di Padova – Dipartimento di Ingegneria Industriale

Corso di Laurea in Ingegneria Aerospaziale

Relazione per la prova finale  
**«*Geometric and CFD analysis of a NACA  
65 blade row for axial compressors*»**

Tutor universitario:

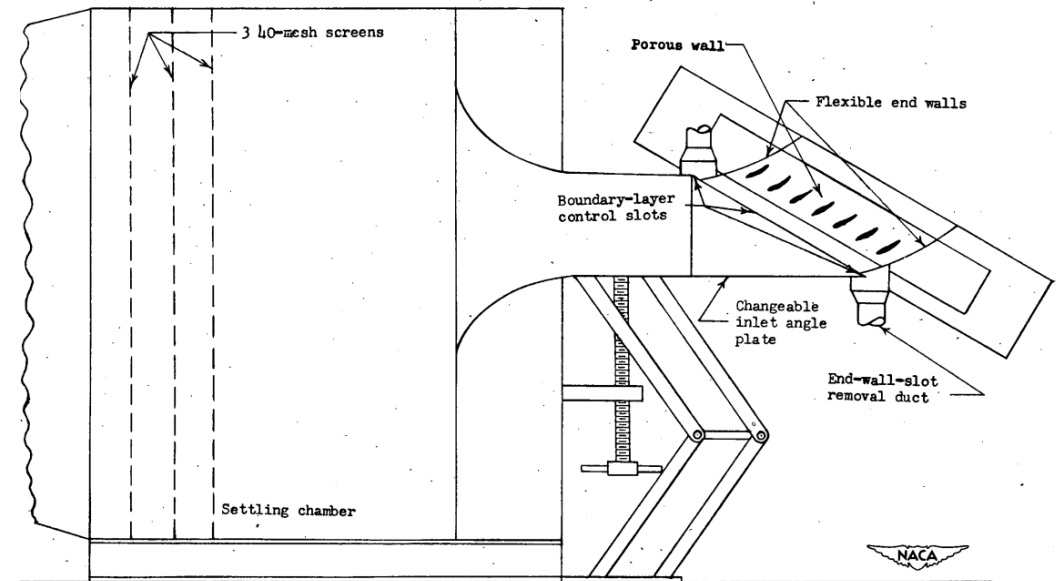
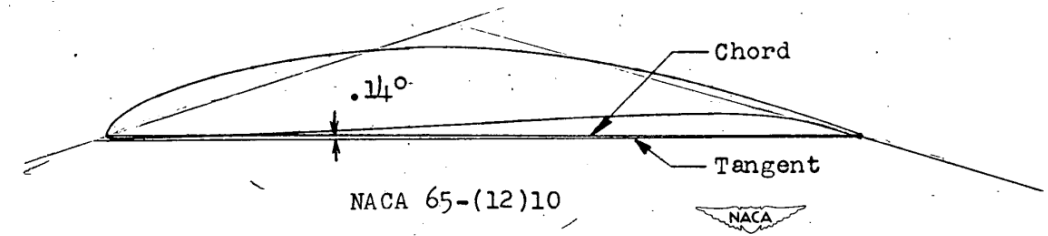
Prof. Ing. Ernesto Benini

Laureando:

Edoardo Petrin

Padova, 18/07/2025

1. Introduzione e obiettivi
2. Ricostruzione della geometria
3. Preparazione e validazione mesh
4. Valutazione agli angoli di attacco
5. Conclusioni



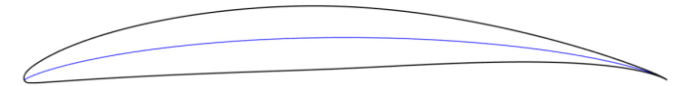
## 1.1 Obiettivi

Studiare in CFD il comportamento del profilo NACA 65-(12)10 al variare dell'angolo di attacco

Identificare le condizioni di massima efficienza della schiera

→  $\max(L/D)$

Confrontare i risultati con i test sperimentali sviluppati da NACA nel seguente report:



RESEARCH MEMORANDUM  
SYSTEMATIC TWO-DIMENSIONAL CASCADE TESTS OF  
NACA 65-SERIES COMPRESSOR  
BLADES AT LOW SPEEDS  
By L. Joseph Herrig, James C. Emery,  
and John R. Erwin

### 2.1 Linea Media

Definizione per via analitica

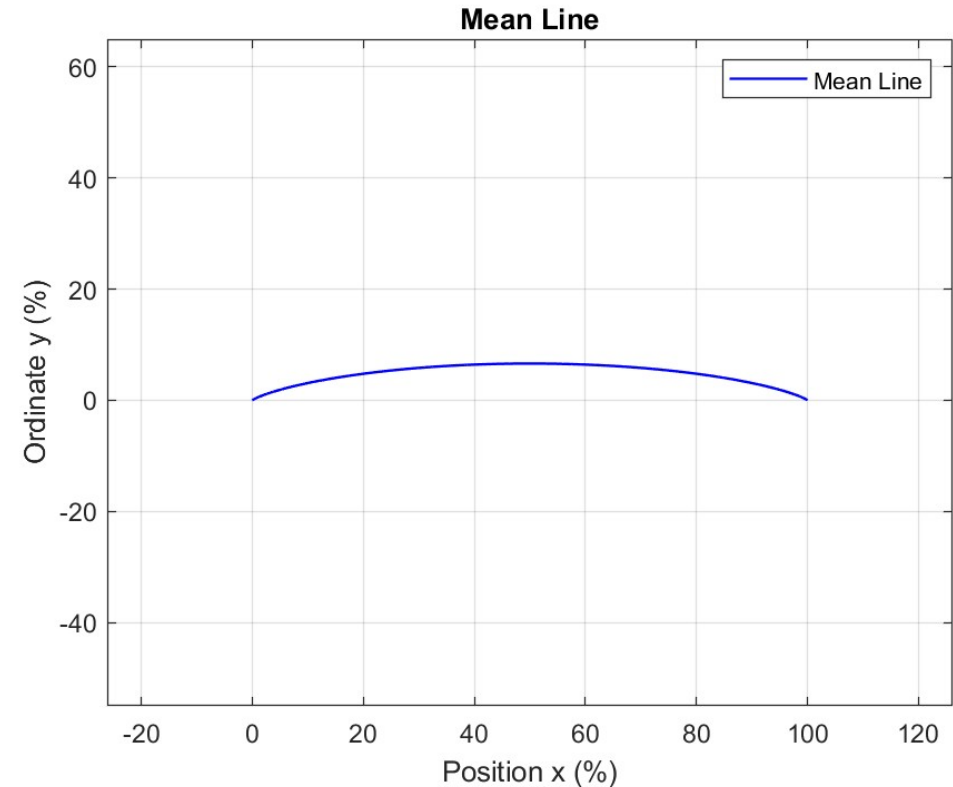
Configurazione logaritmica

$$\frac{y}{c} = -\frac{C_{L0}}{4\pi} \left[ \left(1 - \frac{x}{c}\right) \ln \left(1 - \frac{x}{c}\right) + \left(\frac{x}{c}\right) \ln \left(\frac{x}{c}\right) \right]$$

→  $C_{L0} = 1.2$

→  $\frac{t_{max}}{c} = 10 \%$

→  $\frac{x_{t_{max}}}{c} = 50 \%$

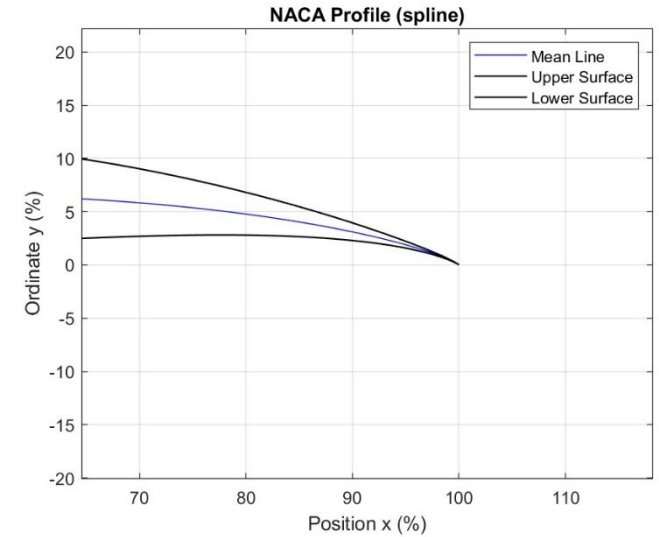
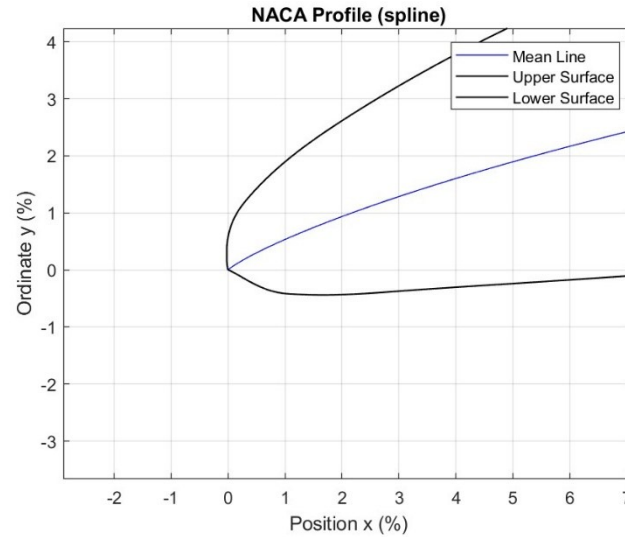
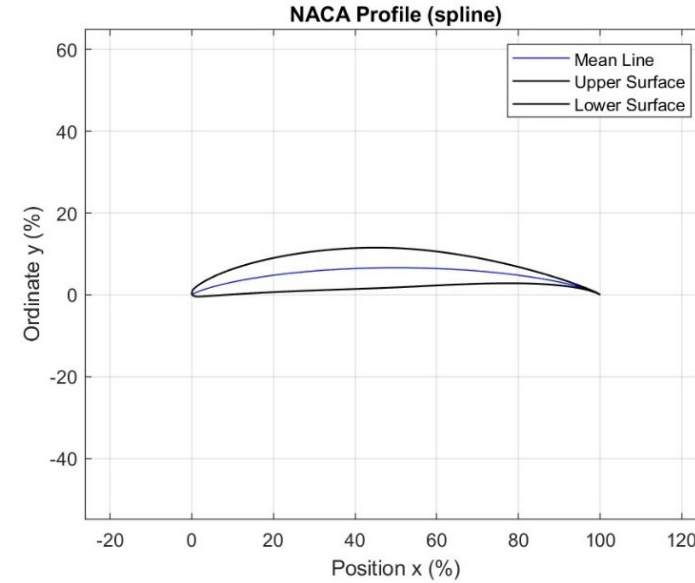


## 2.2 Distribuzione di spessori

Interpolazione spessori report

Somma alla linea media  
normalmente alla tangente locale

Station, x	Ordinates, ±y	
	65(216)-010 airfoil combined with $y = 0.0015x$	Derived 65-010 airfoil
0	0	0
.5	.752	.772
.75	.890	.932
1.25	1.124	1.169
2.5	1.571	1.574
5.0	2.222	2.177
7.5	2.709	2.647
10	3.111	3.040
15	3.746	3.666
20	4.218	4.143
25	4.570	4.503
30	4.824	4.760
35	4.982	4.924
40	5.057	4.996
45	5.029	4.963
50	4.870	4.812
55	4.570	4.530
60	4.151	4.146
65	3.627	3.682
70	3.038	3.156
75	2.451	2.584
80	1.847	1.987
85	1.251	1.385
90	.749	.810
95	.354	.306
100	.150	0
L.E. radius	.666	.687



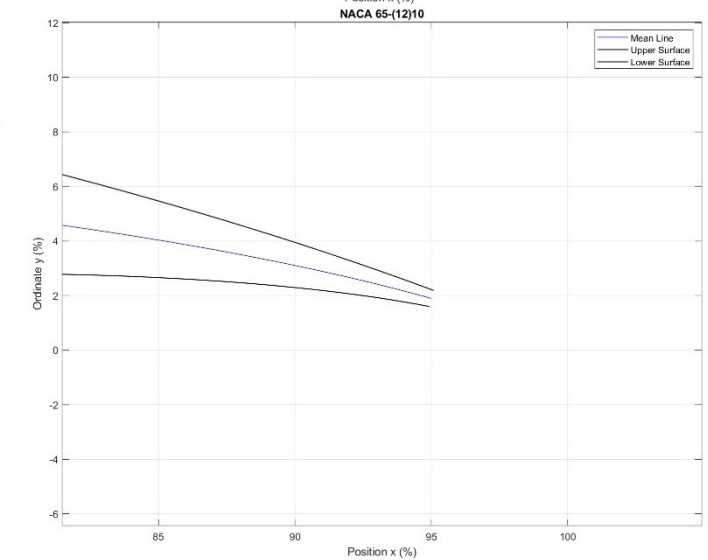
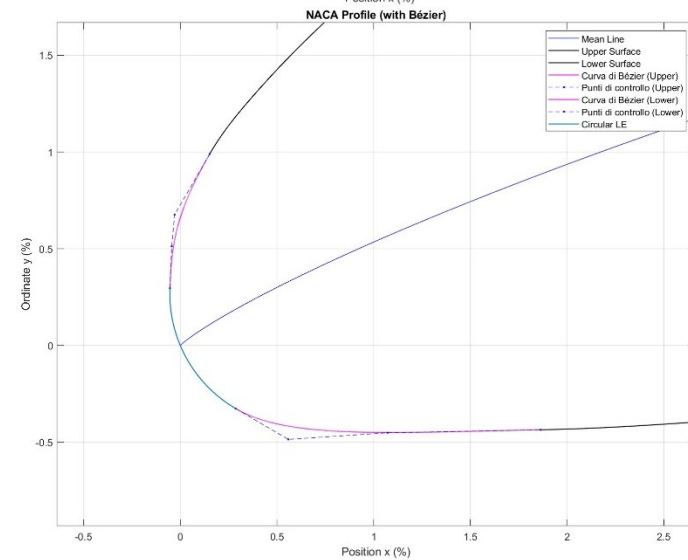
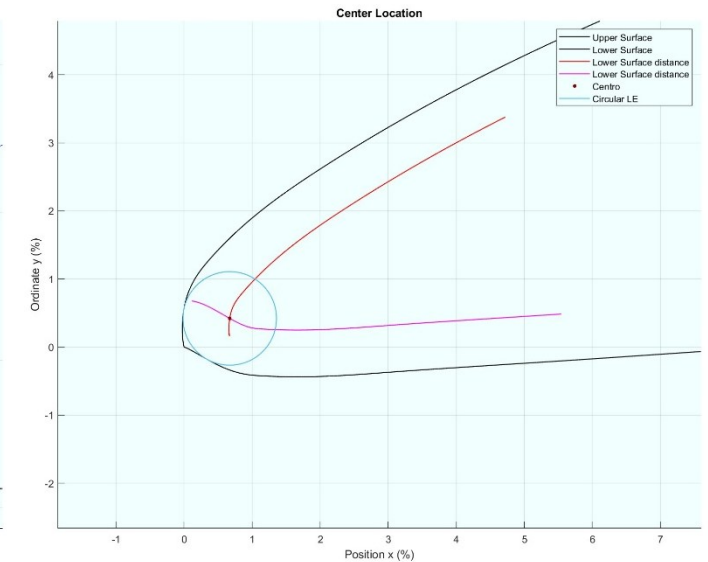
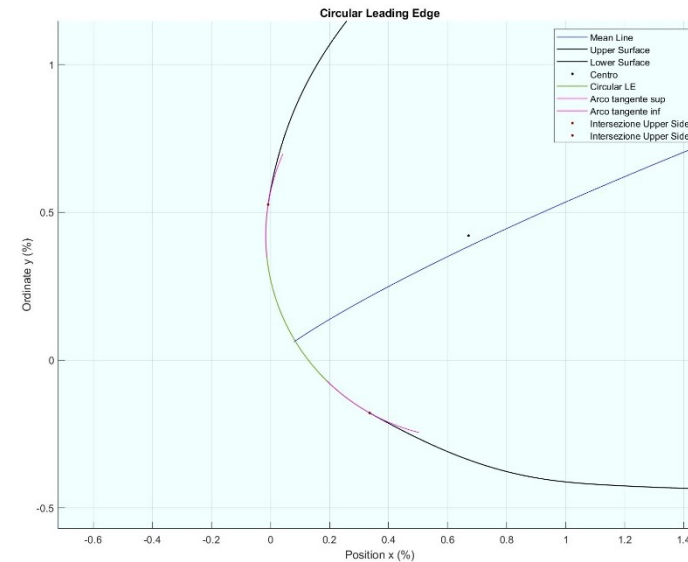
### 2.3 Arrotondamento LE e TE

LE per *trial and error*

LE con circonferenza  
inscritta ( $\frac{R}{c} = 0.687\%$ )

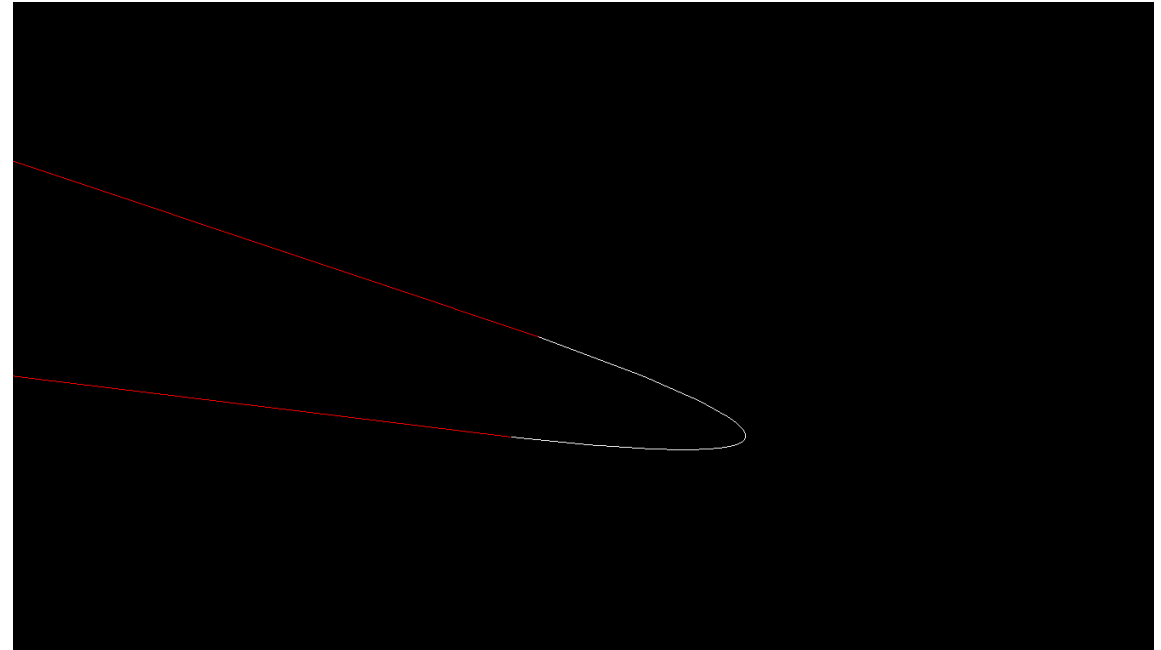
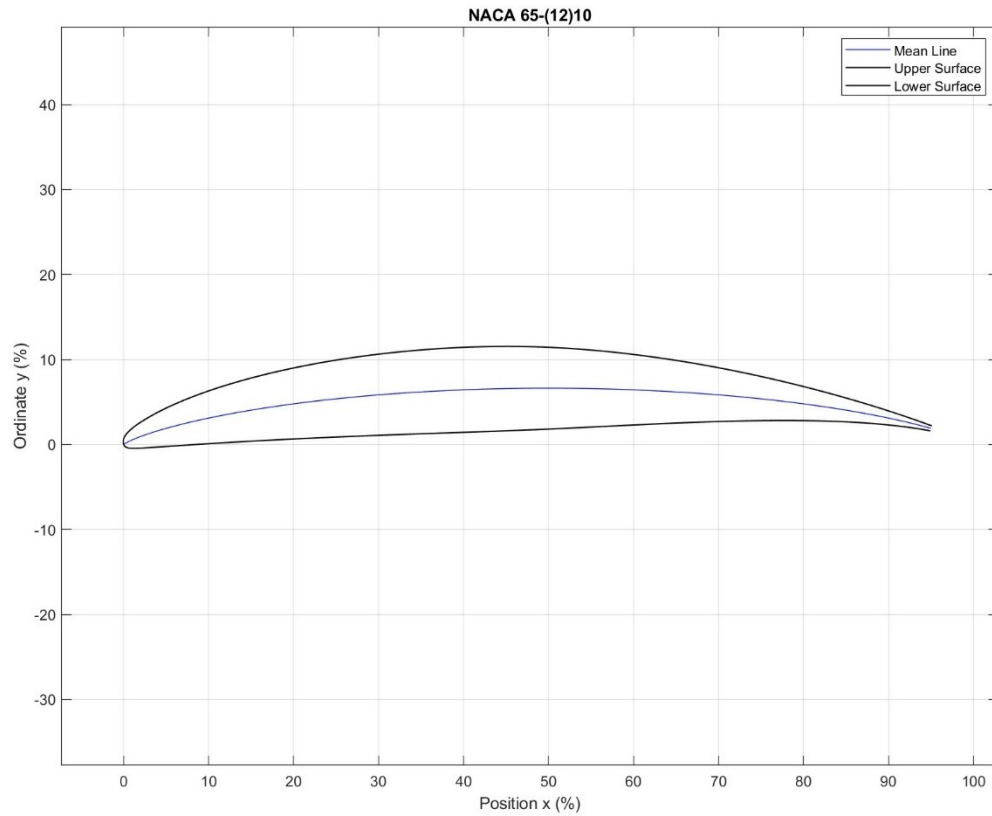
LE con circonferenza  
passante per (0,0) e *Bezier*

TE tagliato al 95% e  
arrotondato con *Bezier*



### 2.3 Geometria finale del profilo

$$\theta_c = 42.5199^\circ$$



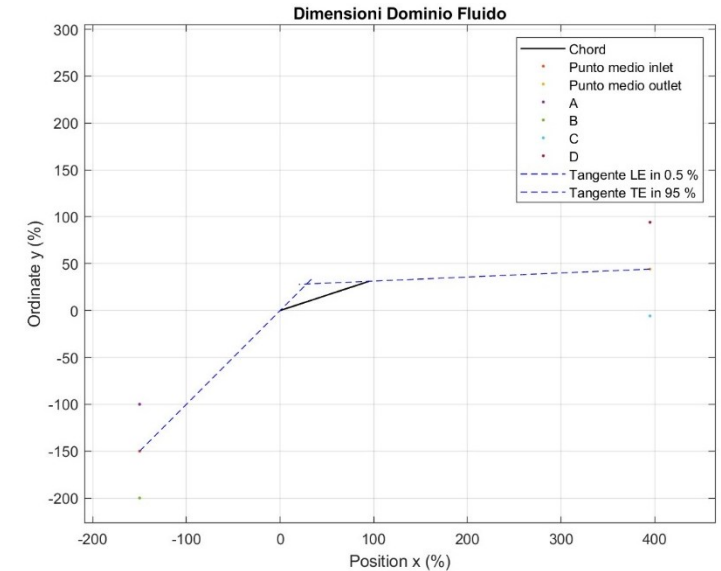
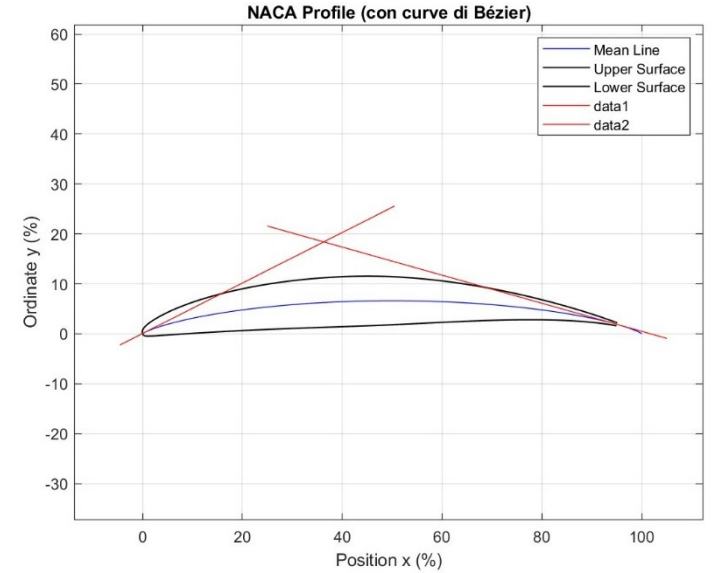
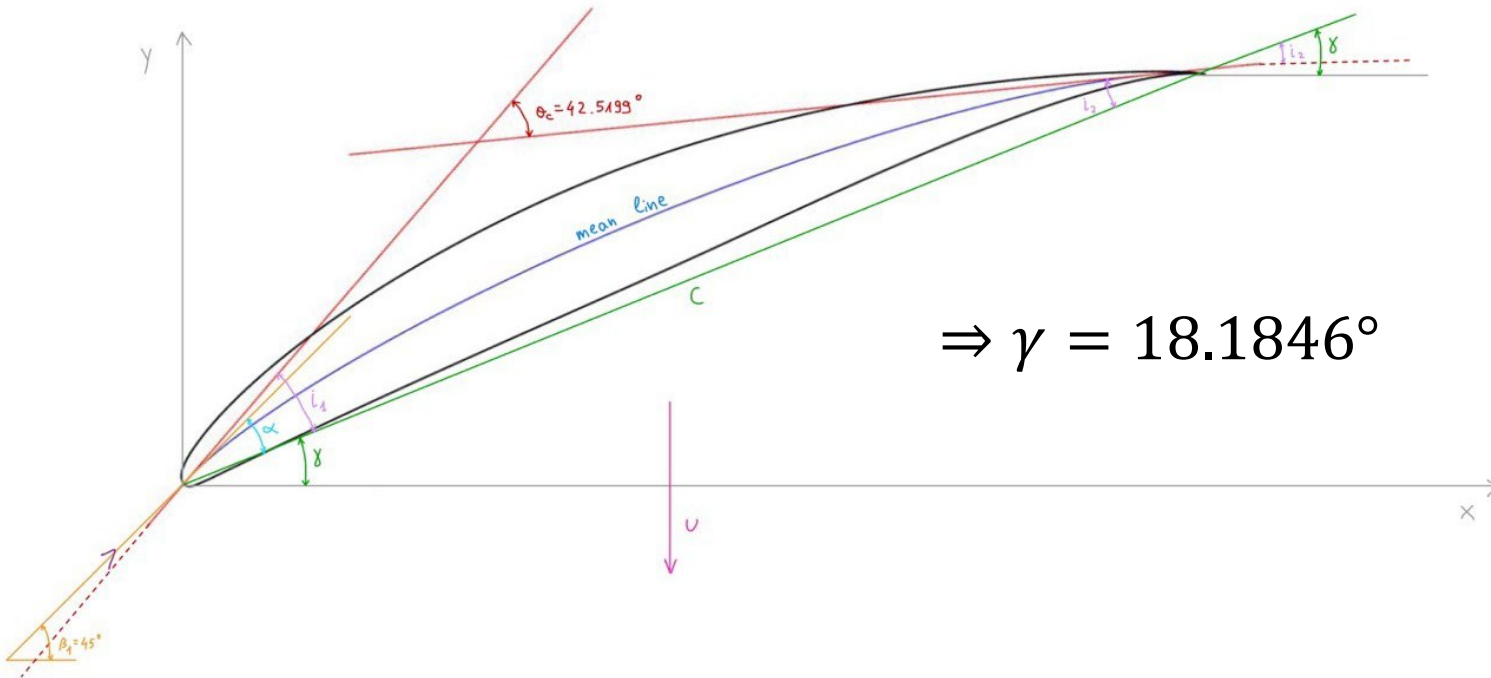
## 2.3 Definizione dominio fluido

Scelta delle condizioni di test

$\beta_1 = 45^\circ$

$\sigma = 1$

$\Rightarrow \gamma = 18.1846^\circ$



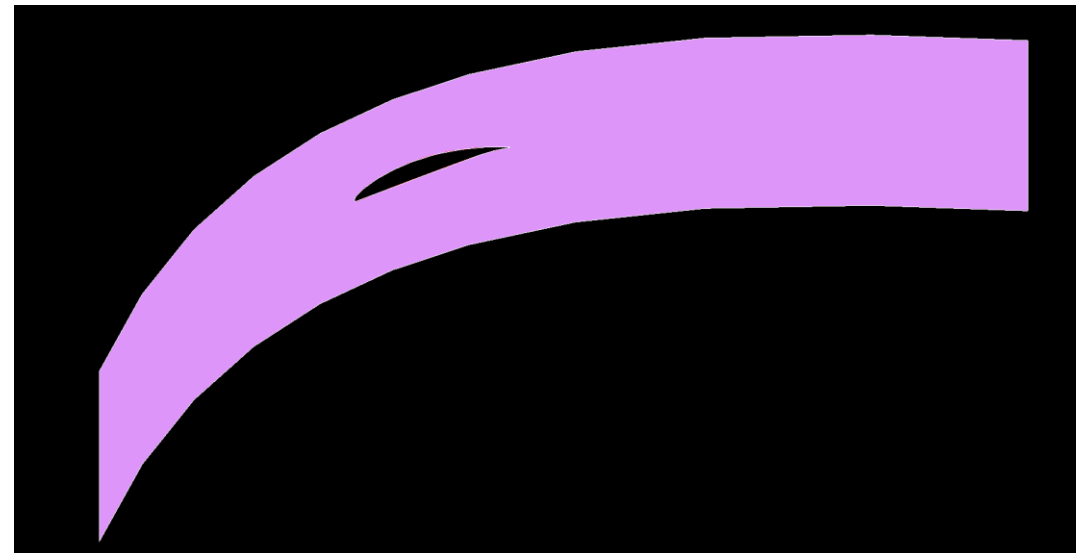
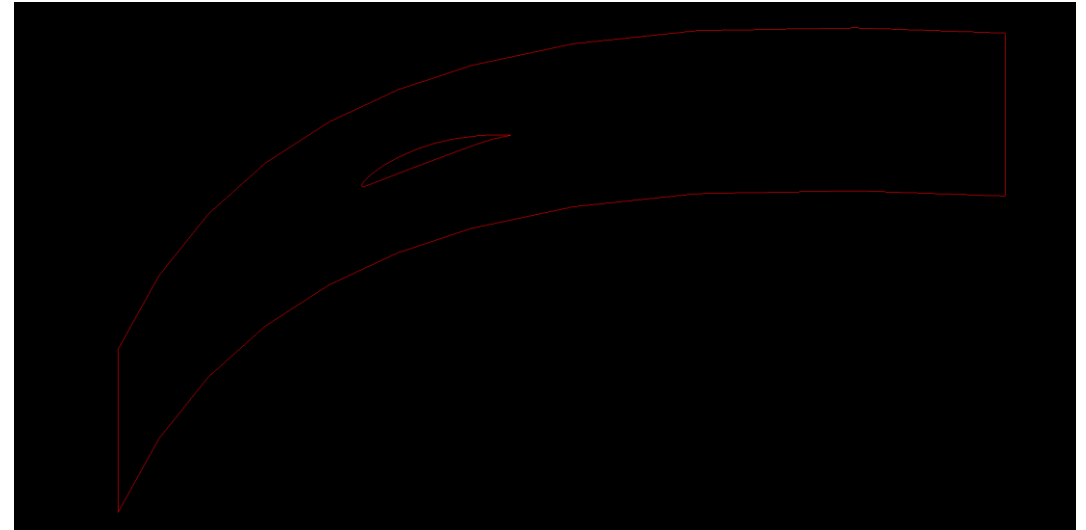
#### 3.1 Creazione dominio fluido

Esportazione 600 punti su Salome

Interpolazione Suction Side,  
Pressure Side, LE e TE

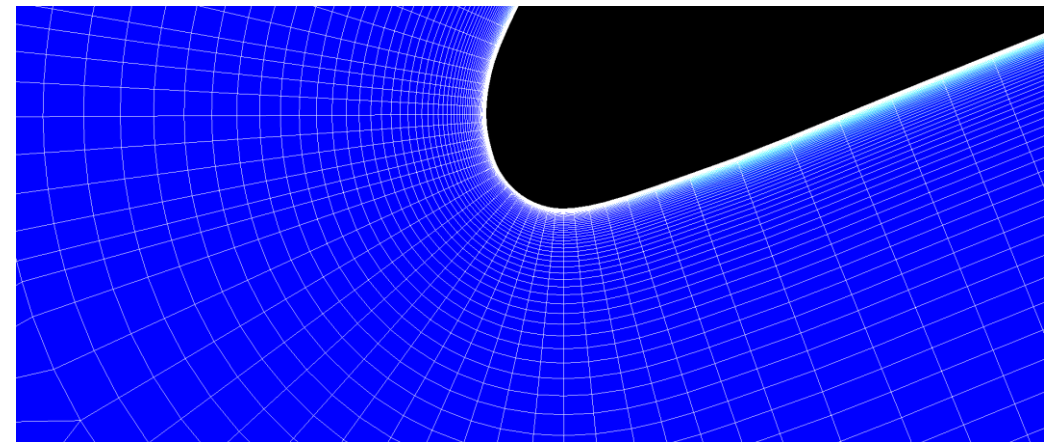
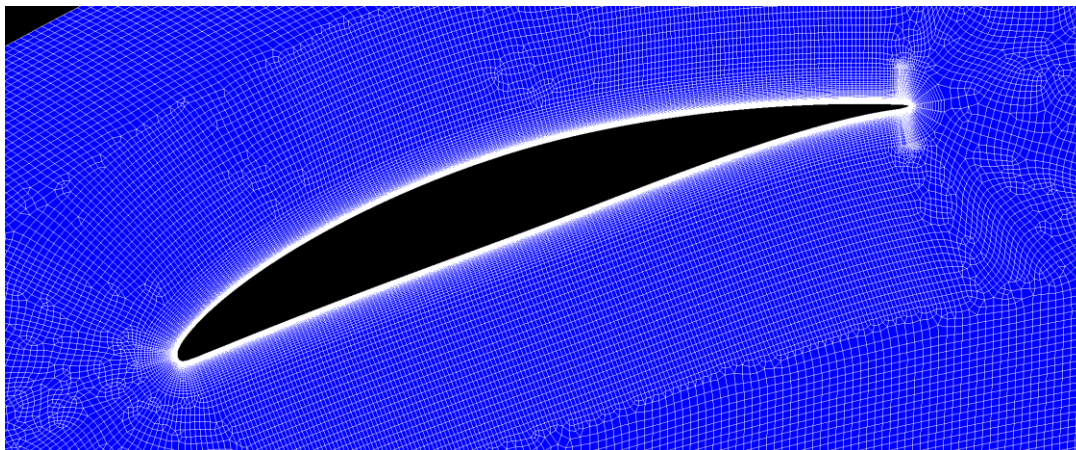
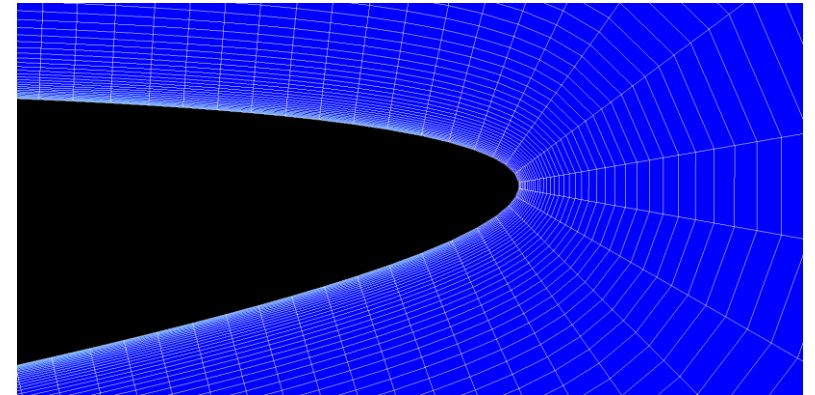
Rotazione profilo e definizione  
punti guida per dominio fluido

Definizione superficie su cui  
creare la mesh



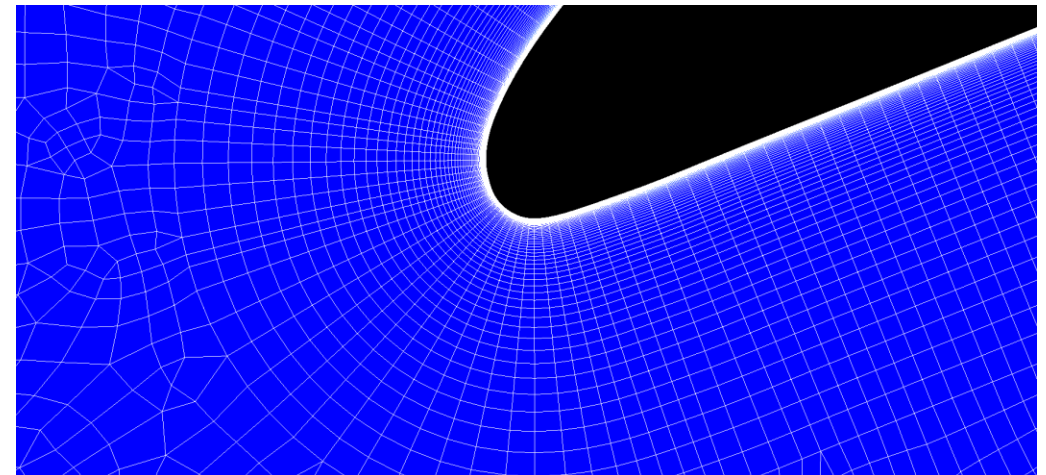
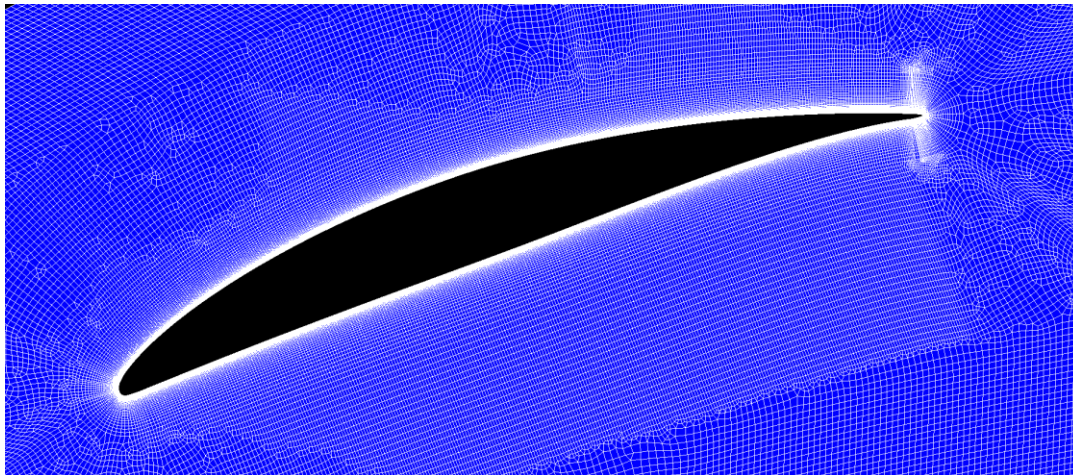
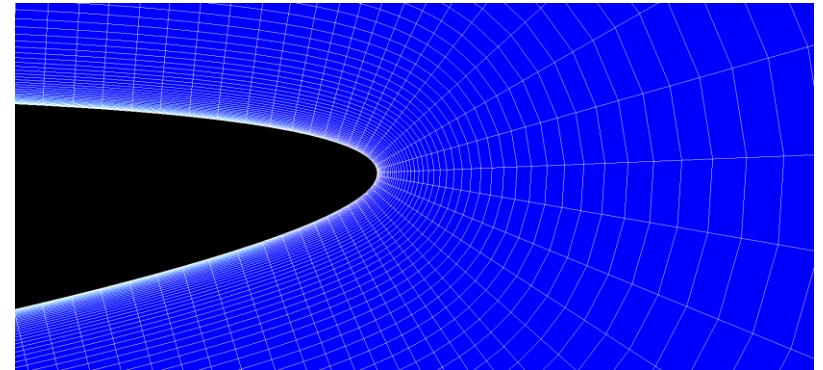
#### 3.2 Mesh fine → Quad-dominated, second order, con viscous layer

- $\max(\text{Aspect Ratio})$  in dominio \ viscous layer = 5.5
- $\max(\text{Aspect Ratio})$  in viscous layer = 161
- $\max(\text{Skewness}) = 1.23$



#### 3.2 Mesh *very fine* → Quad-dominated, second order, con viscous layer

- $\max(\textit{Aspect Ratio})$  in dominio \ viscous layer = 4.1
- $\max(\textit{Aspect Ratio})$  in viscous layer = 165
- $\max(\textit{Skewness}) = 1.14$



#### 3.3 Setup *Fluent*

→ Scala →  $c = 100 \text{ m} \rightarrow 5 \text{ in} = 0.127 \text{ m}$

→ Fluido → Aria a densità costante →

$$\rho = 1.225 \text{ kg/m}^3$$

$$\mu = 1.7894 \cdot 10^{-5} \text{ kg/m} \cdot \text{s}$$

→ Modello viscoso SST K- $\omega$

→ Pressione *Inlet* → Pressione atmosferica

→ Velocità *Inlet* →  $95 \text{ ft/s} = 28.956 \text{ m/s}$

→ Pressione *Outlet* → Pressione atmosferica +  $\Delta p$  \*

→ Periodicità tra *Upper side* e *Lower side*

→ Metodo di calcolo → Coupled, II ordine

$$\left\{ \begin{array}{l} Re = \frac{\rho v c}{\mu} \approx 252.000 \\ Re_{test} = 245.000 \end{array} \right.$$

#### 3.3.1 Valutazione Pressione all'Outlet

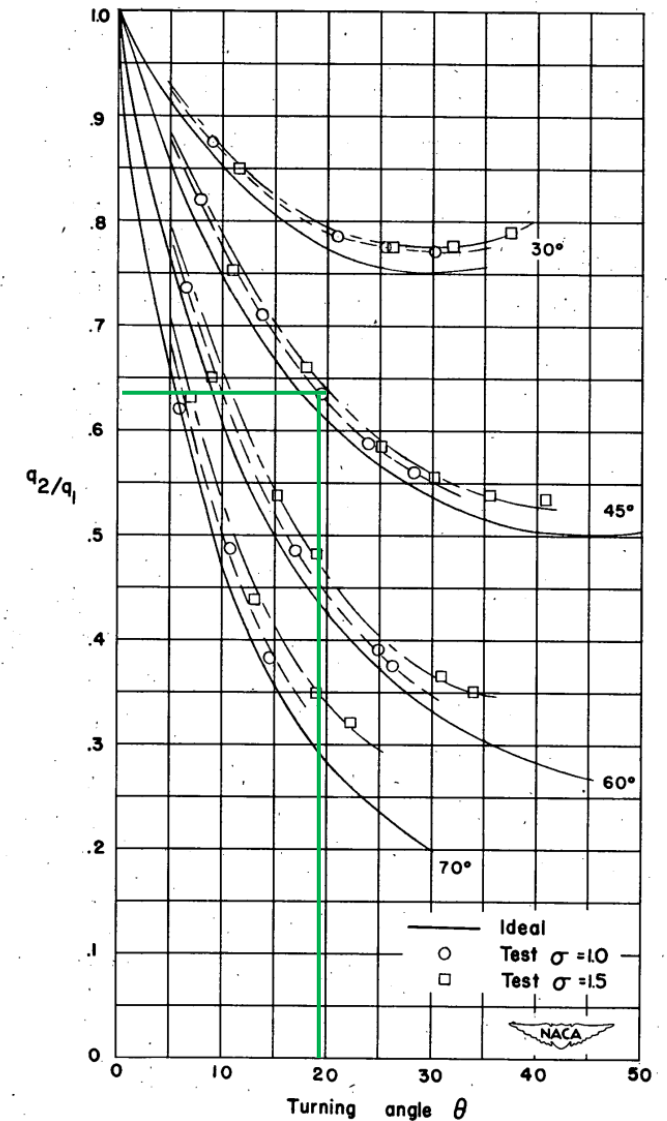
→ Noto il *turning angle*  $\theta = 19.6^\circ$

→ Valutazione tramite diagramma di  $\frac{q_2}{q_1} \approx 0.63$

$$\rightarrow q_1 = \frac{1}{2} \rho c_1^2 = 513.55 \text{ Pa}$$

$$\rightarrow \frac{\Delta p}{q_1} = 1 - \frac{q_2}{q_1} = 0.37 \Rightarrow p_{rel,outlet} = 190.0137 \text{ Pa}$$

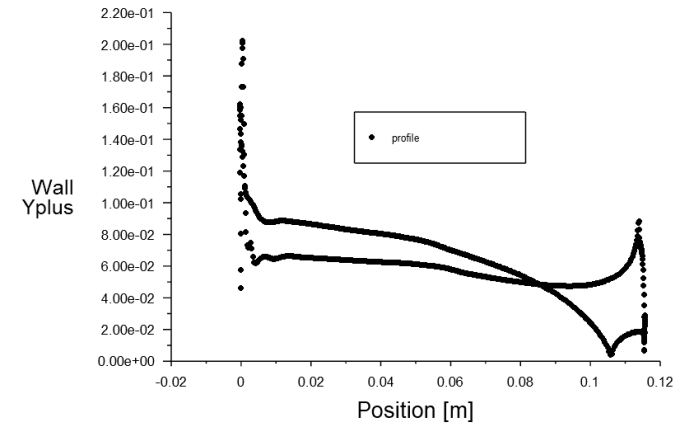
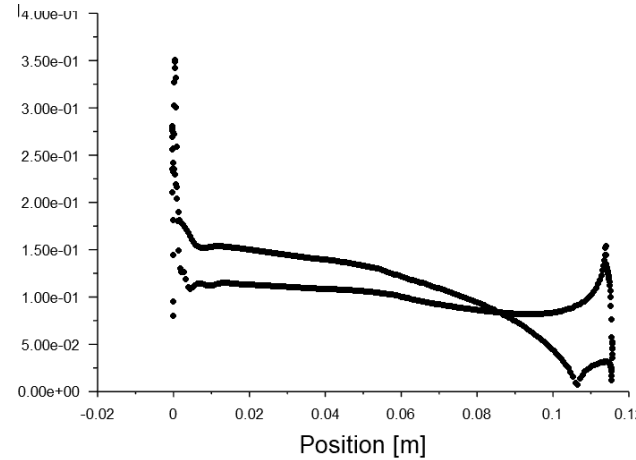
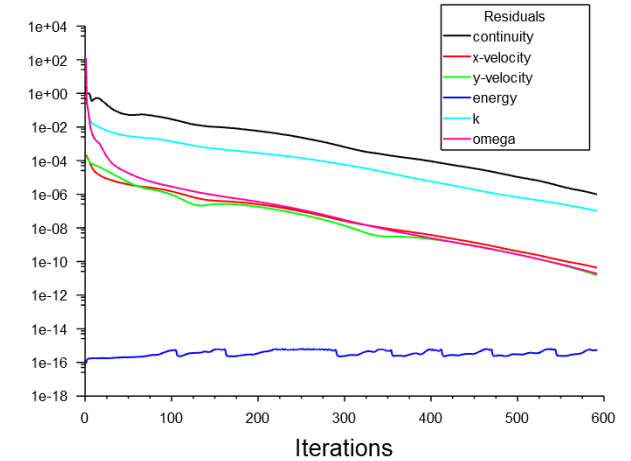
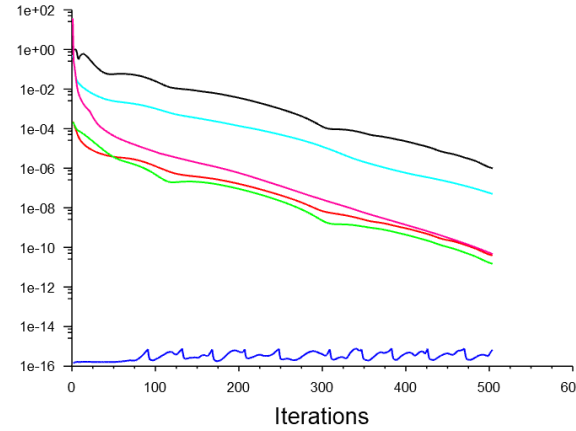
in condizioni di progetto



## 3.4 Validazione mesh

Confronto risultati mesh *fine*  
e *very-fine* in condizioni di  
progetto

Verifica che il problema è mesh-  
*independent* (errore < 2%)



Mesh *fine*

Mesh *very-fine*

#### 3.4 Validazione mesh

$$\frac{|\beta_{2,fine} - \beta_{2,veryfine}|}{\beta_{2,veryfine}} = 0.64 \%$$

$$\frac{|c_{2,fine} - c_{2,veryfine}|}{c_{2,veryfine}} = 0.04 \%$$

Scelta della mesh: *very fine*

Mesh very-fine



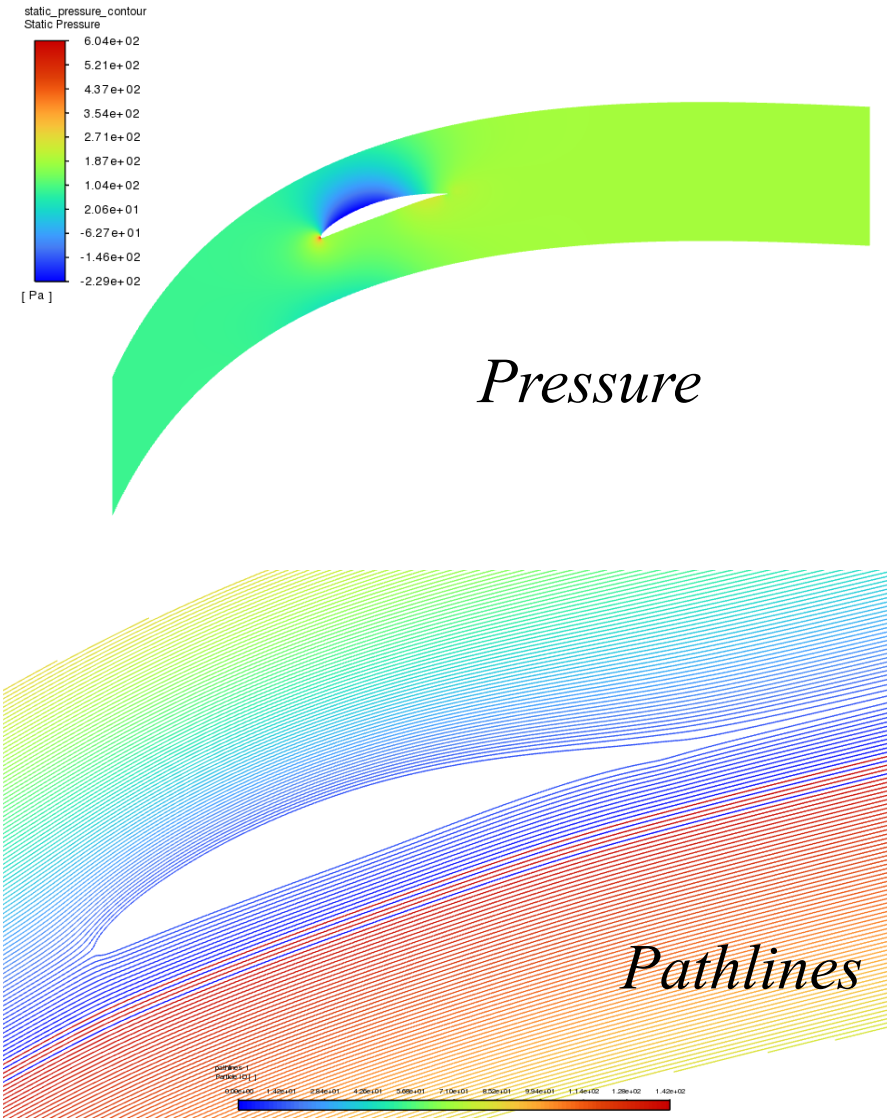
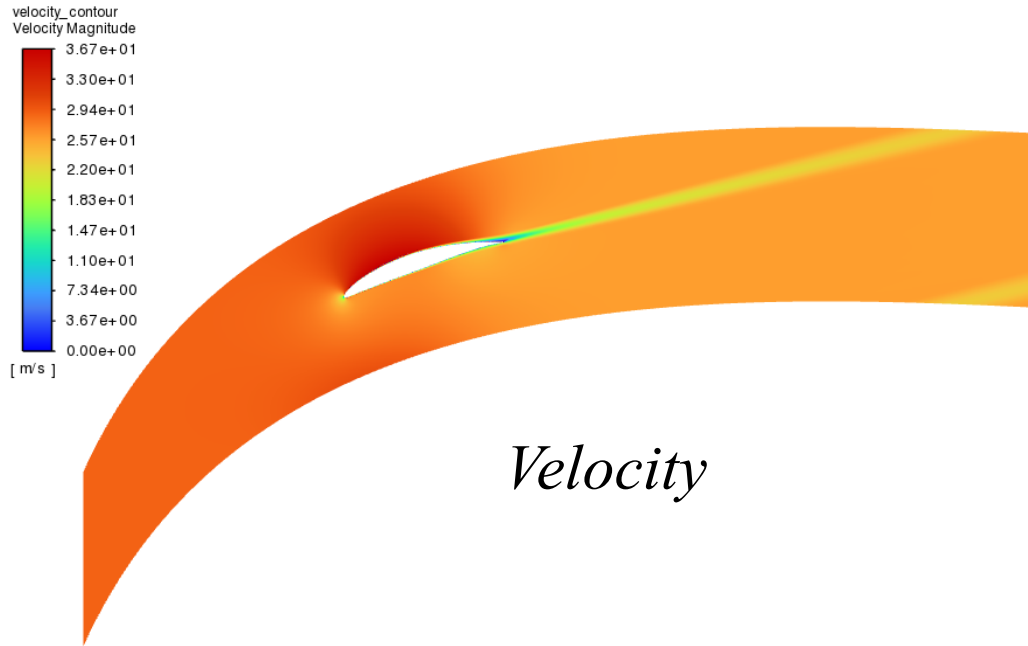
"Surface Integral Report"	
Area-Weighted Average Velocity Angle	[deg]
-----	
outlet	13.642741
Area-Weighted Average Velocity Magnitude	[m/s]
-----	
outlet	25.730389

Mesh fine



"Surface Integral Report"	
Area-Weighted Average Velocity Angle	[deg]
-----	
outlet	13.554594
Area-Weighted Average Velocity Magnitude	[m/s]
-----	
outlet	25.72089

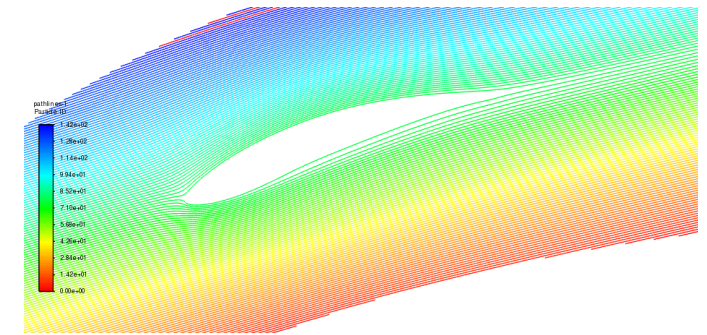
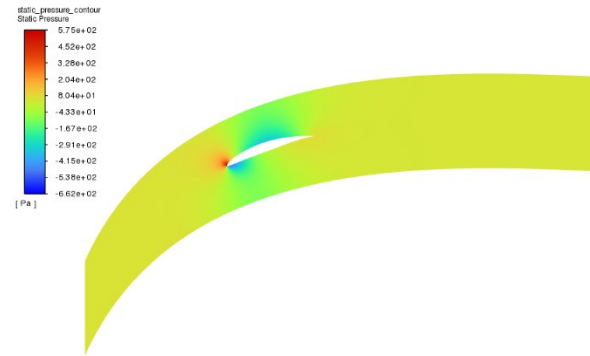
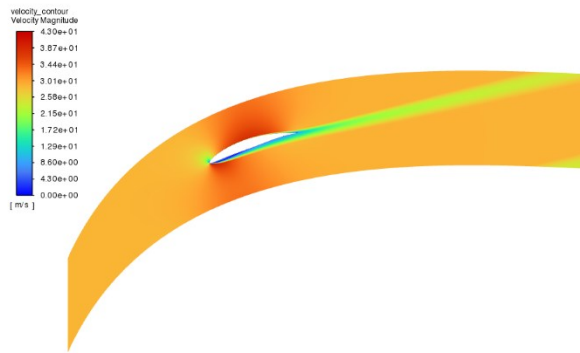
## 4.1 Condizioni di progetto



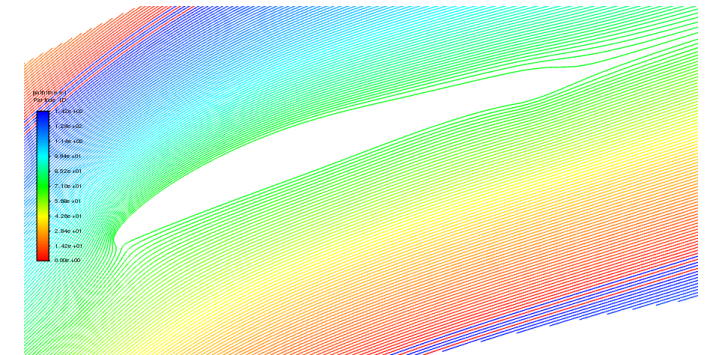
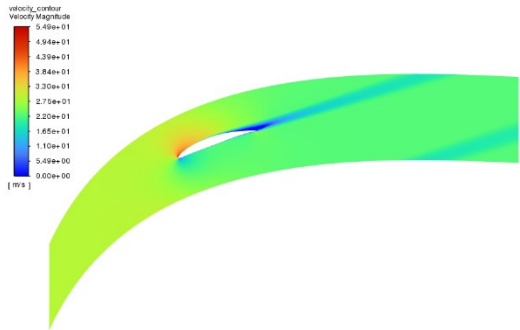
## 4.2 Variazione angolo di attacco e risultati grafici

Alpha

-0.9°



25.1°



*Velocity*

*Pressure*

*Pathlines*

4.2 Valutazione  $C_L, C_D, L/D$

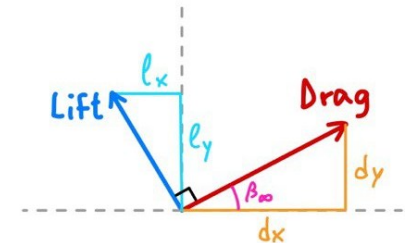
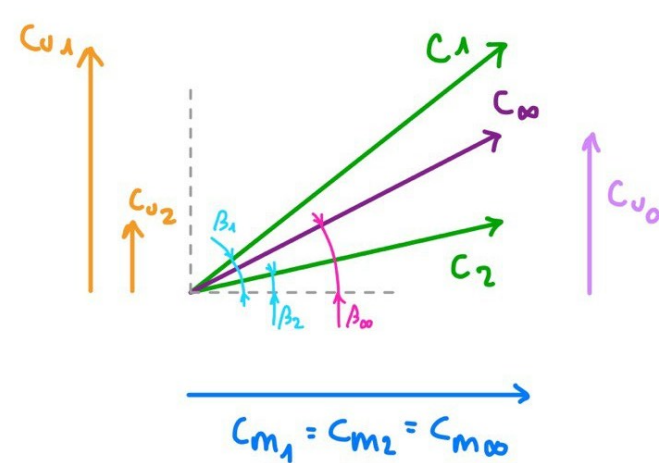
$c_{m,1} = c_1 \cos \beta_1 = c_{m,2} = c_2 \cos \beta_2 = c_{m,\infty} = 25.0044 \text{ m/s}$  in condizioni di progetto

$c_{u,1} = c_1 \sin \beta_1 \quad c_{u,2} = c_2 \sin \beta_2$

$c_{u,\infty} = \frac{c_{u,1} + c_{u,2}}{2}$

$c_{\infty} = \sqrt{c_{m,\infty}^2 + c_{u,\infty}^2}$

$\Rightarrow d_x = l_y = \frac{c_{m,\infty}}{c_{\infty}} \quad , \quad d_y = -l_x = \frac{c_{u,\infty}}{c_{\infty}}$



### 4.3 Risultati

	a	b	c	d	e	f
sigma	1	1	1	1	1	1
beta_1	45	45	45	45	45	45
gamma [°]	18,1846	18,1846	18,1846	18,1846	18,1846	18,1846
alfa [°]	-0,9	5,1	12,1	16,1	21,1	25,1
beta_2 [°]	13,184600	10,684600	10,6846	10,984600	12,984600	17,384600
theta [°]	4,1	12,6	19,6	23,3	26,3	25,9
q_1	513.55	513.55	513.55	513.55	513.55	513.55
q_2/q_1	0,89	0,725	0,63	0,59	0,575	0,58
p_stat_outlet	56,490564	141,226411	190,013717	210,555740	218,258999	215,691246
inlet_x	0,954841	0,918553	0,863531	0,826250	0,774010	0,727957
inlet_y	0,297118	0,395299	0,504296	0,563304	0,633173	0,685623
beta_2	12,974483	12,955881	13,642741	14,264227	15,465956	17,257845
theta [°]	4,310117	10,328719	16,641859	20,020373	23,818644	26,026755
c_2	28,372576	27,292318	25,730389	24,685989	23,254330	22,072476
c_infinito	28,644083	28,010126	27,056356	26,415290	25,550026	24,871033
vers_x_drag	0,965238	0,949571	0,924160	0,905721	0,877191	0,847521
vers_y_drag	0,261371	0,313551	0,382005	0,423874	0,480142	0,530762

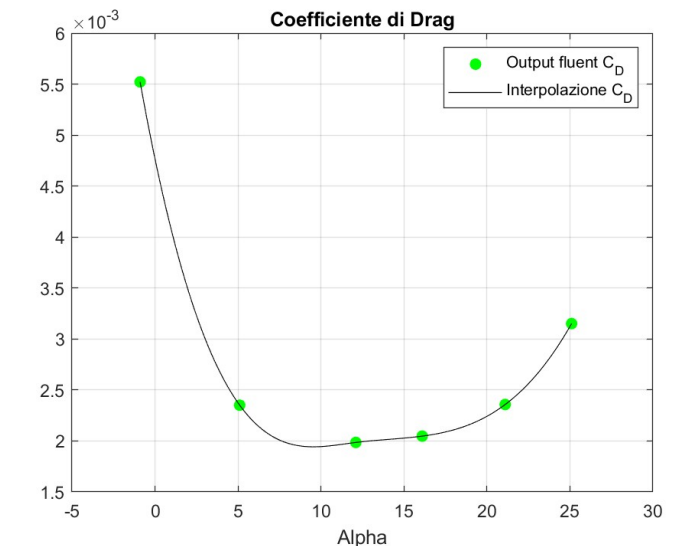
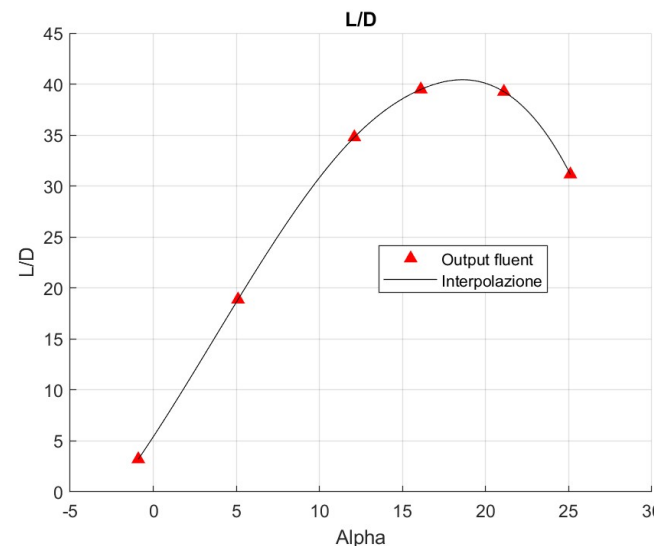
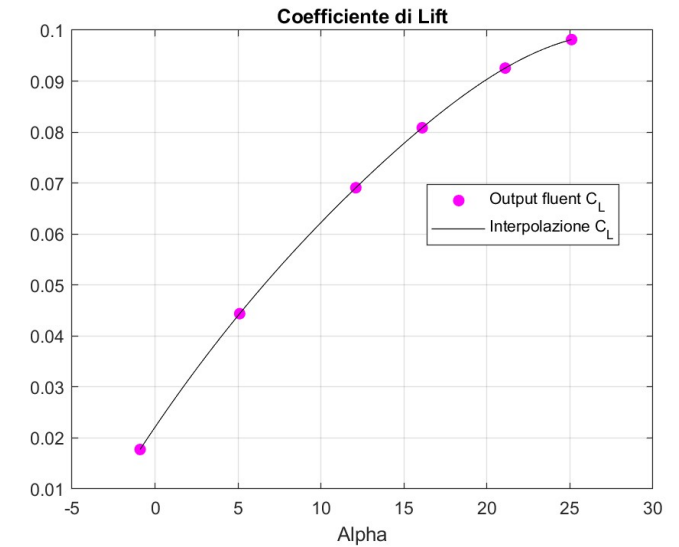
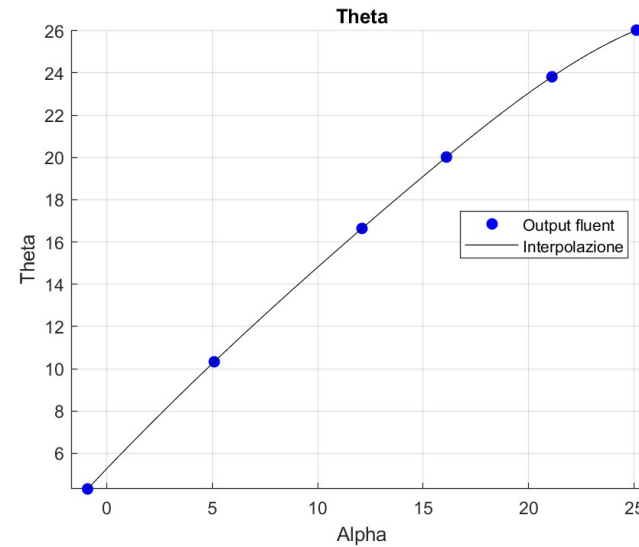
## 4.3 Risultati

### Osservazioni su curva L/D

Verso le condizioni di stallo negativo e positivo si verifica un brusco calo nell'efficienza

Per  $\alpha = 5^\circ \div 10^\circ$  poco drag ma anche poco lift  $\Rightarrow$  efficienza cresce ma non ha valori alti

Punto di max efficienza prima dello stallo (elevato lift ma basso drag)

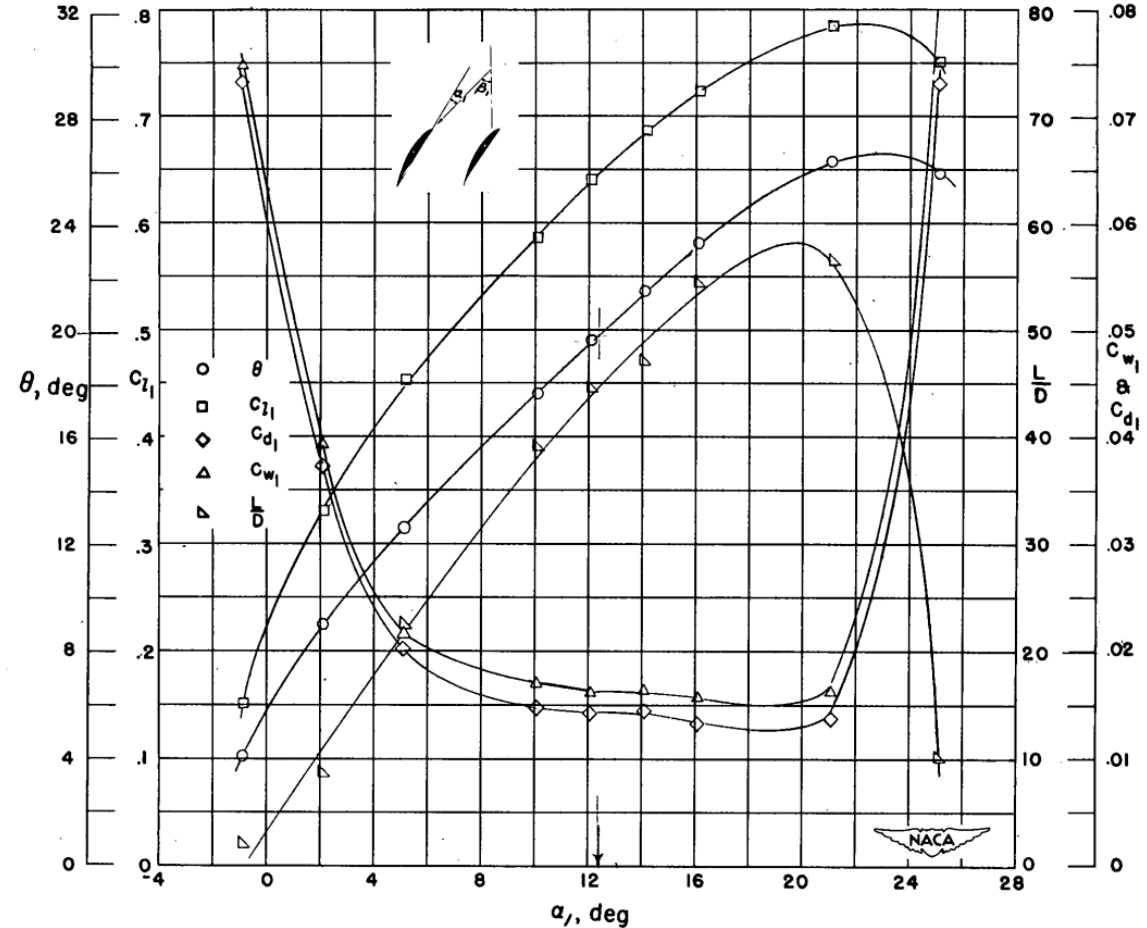


## 4.4 Confronto con valori sperimentali

Affidabilità limitata verso  
condizioni di stallo

L/D minore (probabilmente  
legato all'arrotondamento di  
LE e TE)

	Angolo_Attacco	Scostamento_L_D_%	Scostamento_Theta_%
1	-0.9000	60.6943	5.1248
2	5.1000	-16.0953	-18.0260
3	12.1000	-21.8127	-15.0926
4	16.1000	-27.5569	-14.0757
5	21.1000	-30.5288	-9.4348
6	25.1000	211.4451	0.4894



(g) Section characteristics; arrow shows design angle of attack.

Figure 30.- Concluded.

### 5 Conclusioni

#### Vantaggi e limiti delle simulazioni numeriche

- Permettono analisi ad ampio spettro di condizioni con brevi tempi e bassi costi
- Non sostituiscono i test sperimentali, ma ne sono un complemento

#### Possibili miglioramenti

- Valutazione con più accuratezza delle ipotesi di calcolo (es. densità costante, modello di viscosità)
- Raffinamento Mesh (es. lungo la scia)
- Iterazione del processo cambiando la geometria per ottimizzarne le prestazioni

## Bibliografia

L. Joseph Herrig, James C. Emery, John R. Erwin, *Systematic two-dimensional cascade tests of NACA 65-series compressor blades at low speeds*, NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS, Washigton, 14/09/1951

## Software utilizzati

MATLAB, <https://www.mathworks.com/products/matlab.html>



SALOME <https://www.salome-platform.org/>



ANSYS FLUENT <https://www.ansys.com/it-it>



Grazie per l'attenzione