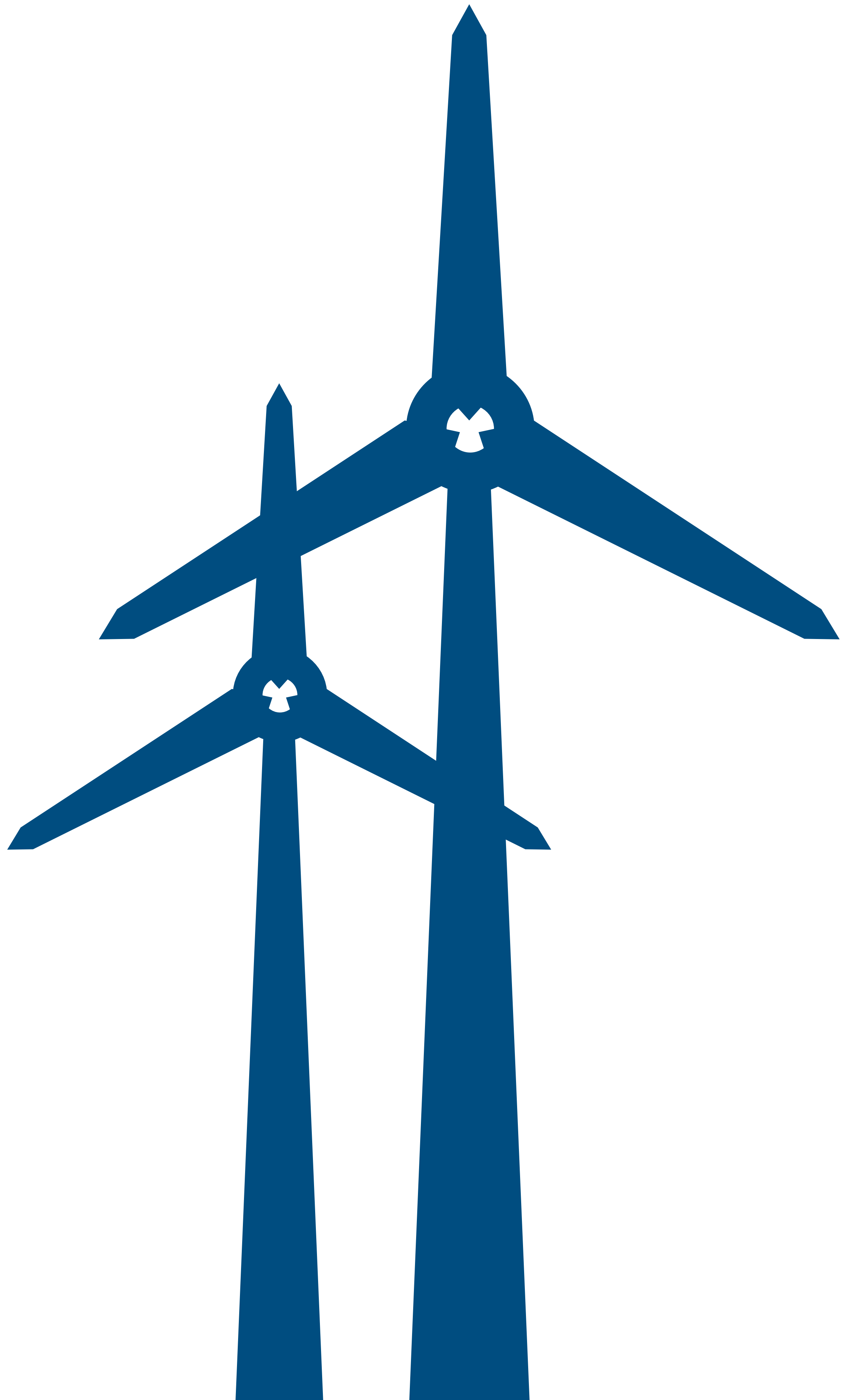
Blade Element Momentum Analysis for HAWT

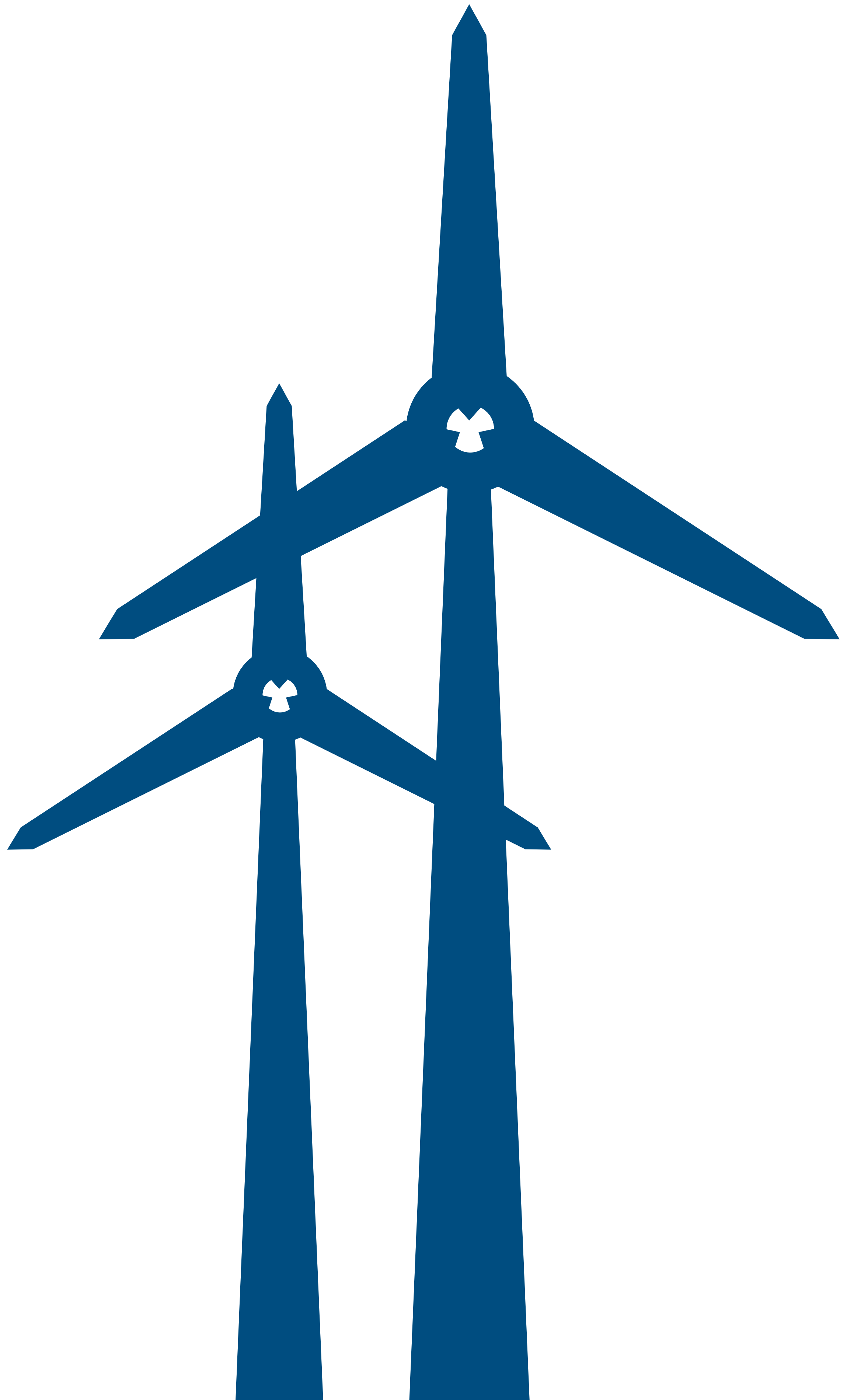


Luisa Di Francesco

Instituto Superior Técnico
Universidade de Lisboa

Summary

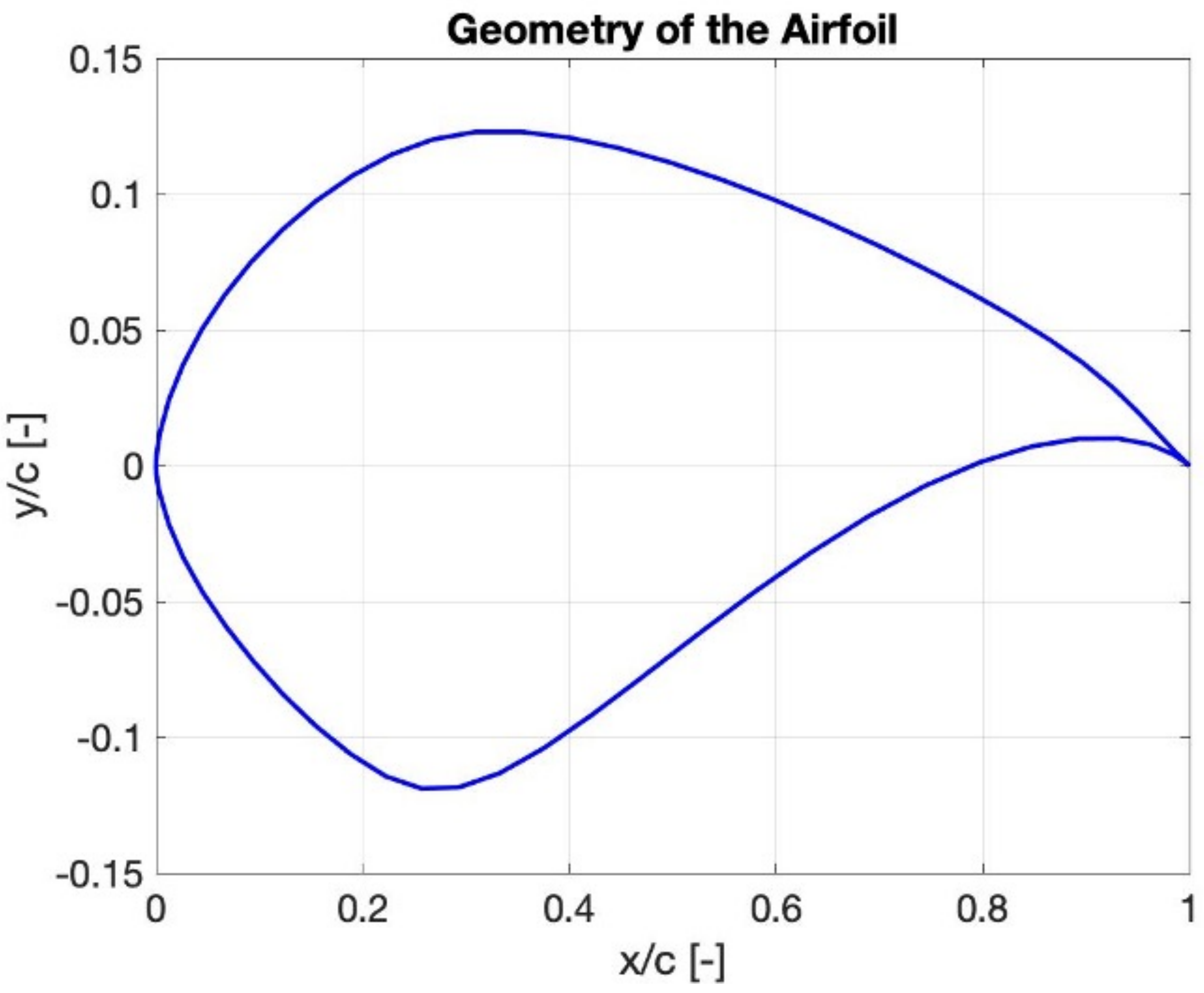
- Data Overview
- Part 1: Inviscid Flow Design
    - Equations
    - Results
- Part 2: Real Flow Design
    - Equations
    - Results
- Part 3: Real Flow Analysis
    - Equations
    - Results
- Conclusion



Data Overview

The provided data are:

- Wind velocity: U = 12 m/s
- Diameter: D = 150 m
- Number of blades: Z = 3
- Tip Speed Ratio: TSR = 5
- Section foil: S818
- Fluid: Air



Part 1: Inviscid Flow Design

No viscous forces, $C_D = 0$

Equations (1/2)

- Dimensionless radial coordinate

$$x = \frac{\Omega r}{U}$$

- Induction factors

$$x = (4a - 1)\sqrt{\frac{1-a}{1-3a}}$$

$$a' = \frac{1-3a}{4a-1}$$

Part 1: Inviscid Flow Design

No viscous forces, $C_D = 0$

Equations (2/2)

- Undisturbed and induced pitch angle

$$tan\beta = \frac{1}{x}$$

$$tan\beta_i = \frac{1-a}{x(1+a')}$$

- Pitch angle

$$\psi = \beta_i - \alpha$$

- Chord

$$\frac{c}{R} = \frac{8\pi x^2}{ZC_L \cdot TSR} \frac{a'}{1-a} sin\beta_i$$

Part 1: Inviscid Flow Design

No viscous forces, $C_D = 0$

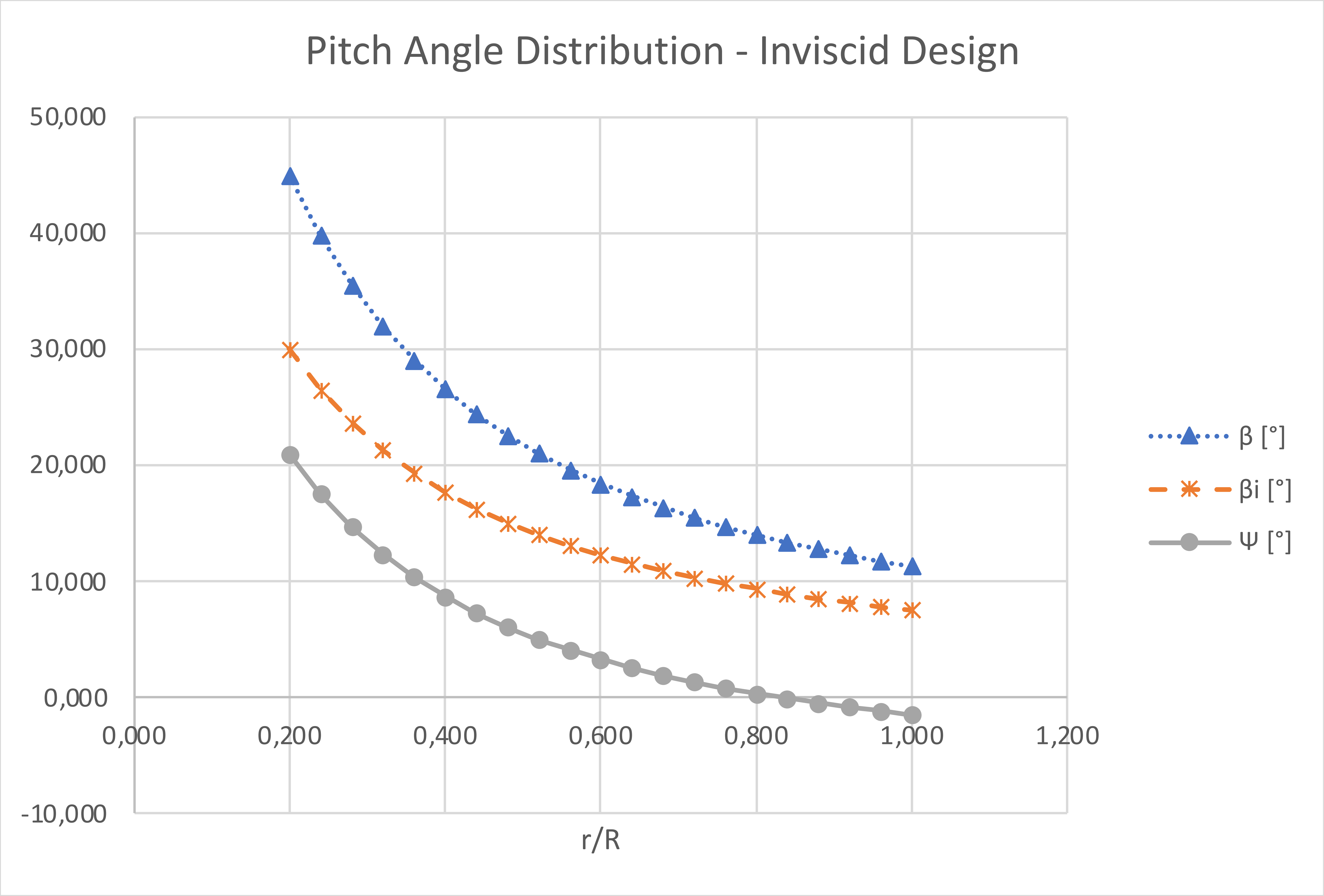
Results (1/4)

r/R	x	a	a'	β [°]	βi [°]	Ψ [°]	c/R
0,200	1,000	0,31699	0,18301	45,000	30,000	21,000	0,15975
0,240	1,200	0,32074	0,13348	39,806	26,537	17,537	0,15075
0,280	1,400	0,32341	0,10137	35,538	23,692	14,692	0,14069
0,320	1,600	0,32535	0,07943	32,005	21,337	12,337	0,13077
0,360	1,800	0,32680	0,06383	29,055	19,370	10,370	0,12148
0,400	2,000	0,32790	0,05235	26,565	17,710	8,710	0,11302
0,440	2,200	0,32875	0,04369	24,444	16,296	7,296	0,10539
0,480	2,400	0,32942	0,03698	22,620	15,080	6,080	0,09855
0,520	2,600	0,32995	0,03170	21,038	14,025	5,025	0,09242
0,560	2,800	0,33039	0,02746	19,654	13,103	4,103	0,08692
0,600	3,000	0,33075	0,02402	18,435	12,290	3,290	0,08198
0,640	3,200	0,33104	0,02118	17,354	11,569	2,569	0,07752
0,680	3,400	0,33129	0,01881	16,390	10,926	1,926	0,07349
0,720	3,600	0,33151	0,01682	15,524	10,349	1,349	0,06984
0,760	3,800	0,33169	0,01512	14,744	9,829	0,829	0,06651
0,800	4,000	0,33184	0,01367	14,036	9,357	0,357	0,06347
0,840	4,200	0,33198	0,01242	13,392	8,928	-0,072	0,06068
0,880	4,400	0,33209	0,01133	12,804	8,536	-0,464	0,05812
0,920	4,600	0,33220	0,01038	12,265	8,177	-0,823	0,05576
0,960	4,800	0,33229	0,00954	11,768	7,846	-1,154	0,05357
1,000	5,000	0,33237	0,00880	11,310	7,540	-1,460	0,05155

Part 1: Inviscid Flow Design

No viscous forces, $C_D = 0$

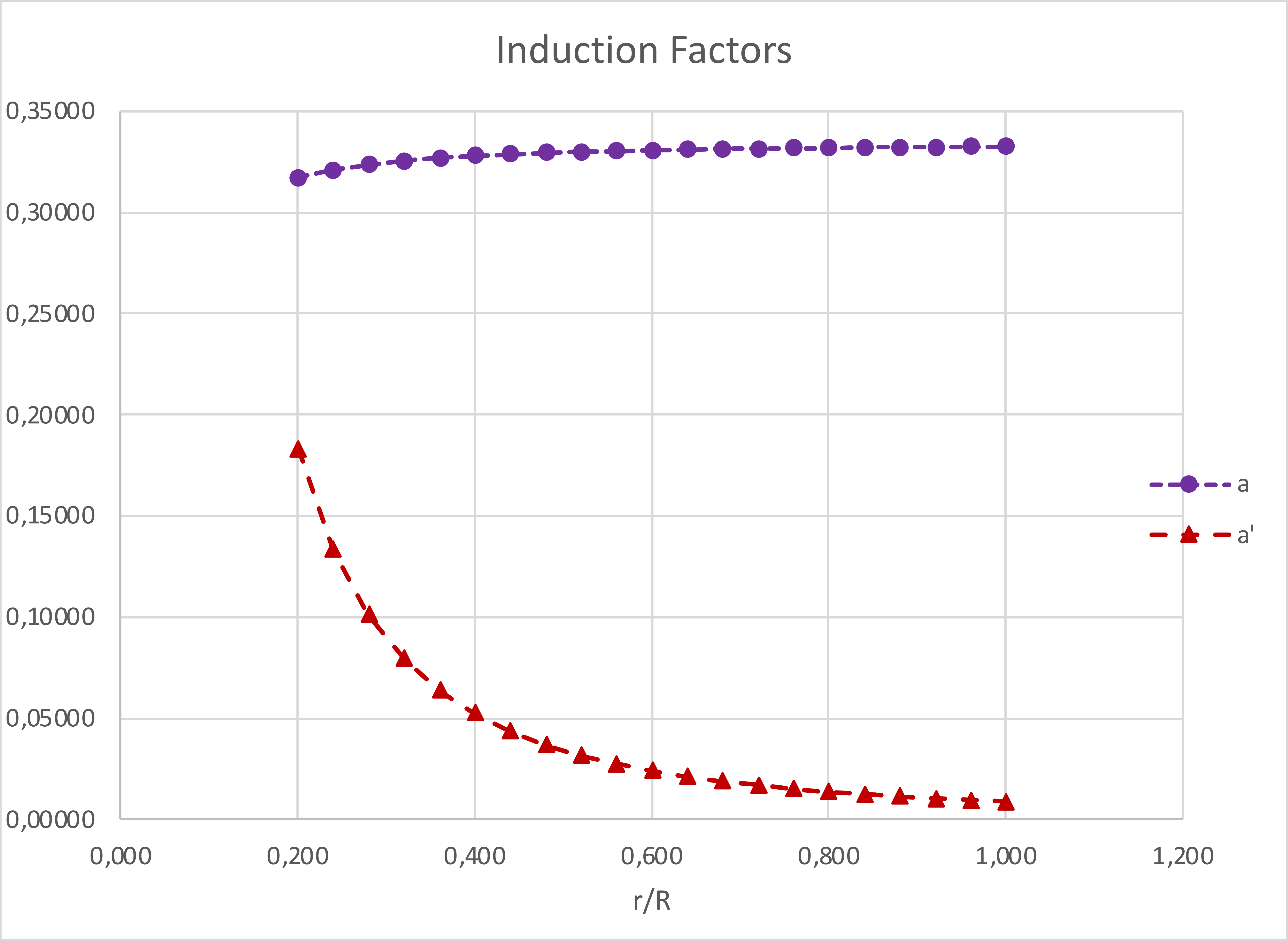
Results (2/4)



Part 1: Inviscid Flow Design

No viscous forces, $C_D = 0$

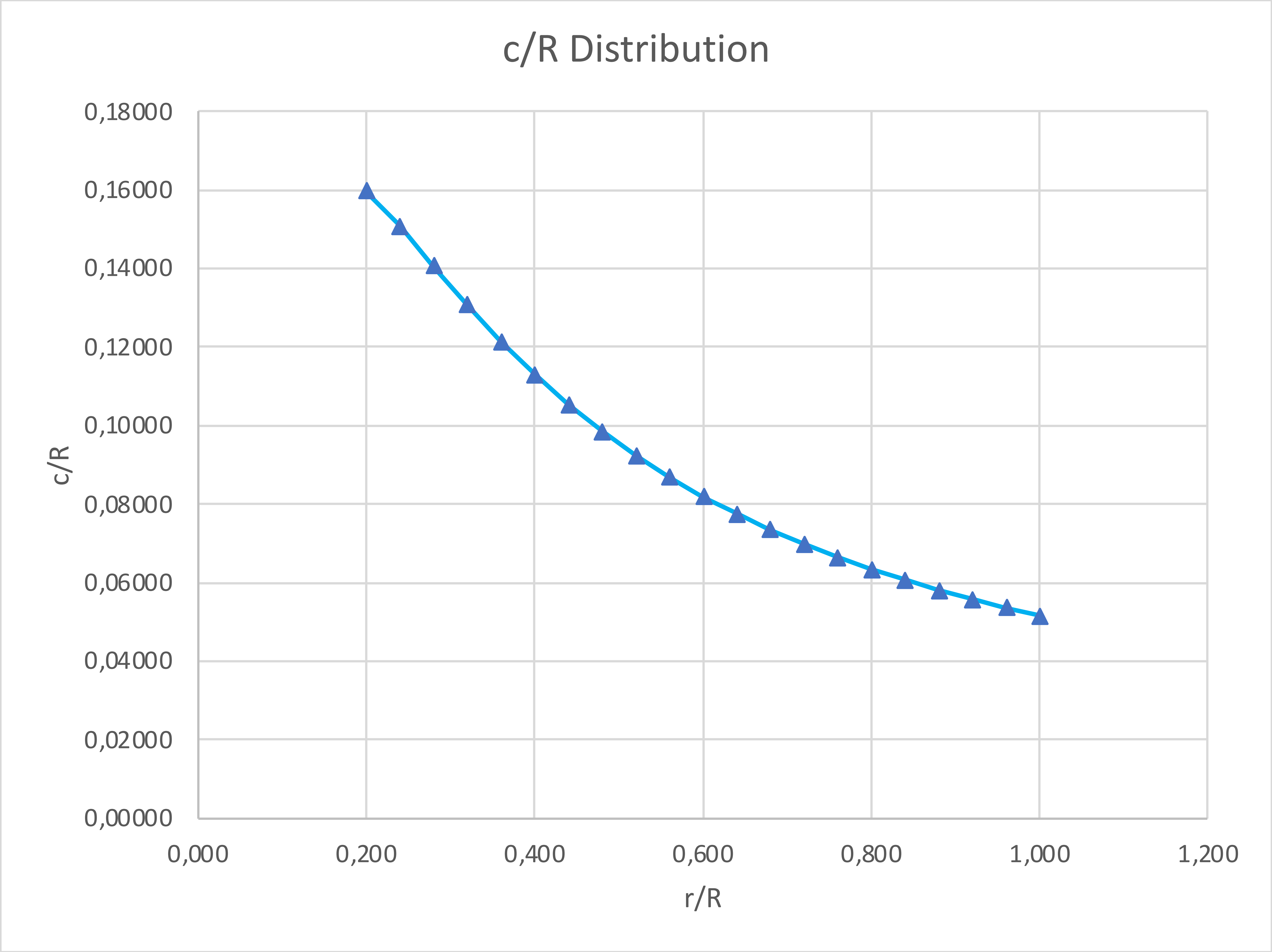
Results (3/4)



Part 1: Inviscid Flow Design

No viscous forces, $C_D = 0$

Results (4/4)



Part 2: Real Flow Design

Drag force present, $C_D \neq 0$

Equations (1/1)

- Induction factors

$$\frac{a}{1-a} = \frac{F cos\beta_i}{8\pi k sin^2\beta_i}(1+\varepsilon tan\beta_i)$$
$$\frac{a'}{1+a'} = \frac{F}{8\pi k cos\beta_i}(1-\varepsilon cot\beta_i)$$

Where:

- $\varepsilon = \frac{C_D}{C_L}$
- $F = \frac{ZcC_L}{r} = F_{Glauert}k$
- $k = \frac{2}{\pi}cos^{-1}\frac{cosh\frac{rf}{R}}{coshf};\ f = \frac{ZR}{2rtan\beta} - \frac{1}{2}$

Part 2: Real Flow Design

Drag force present, $C_D \neq 0$

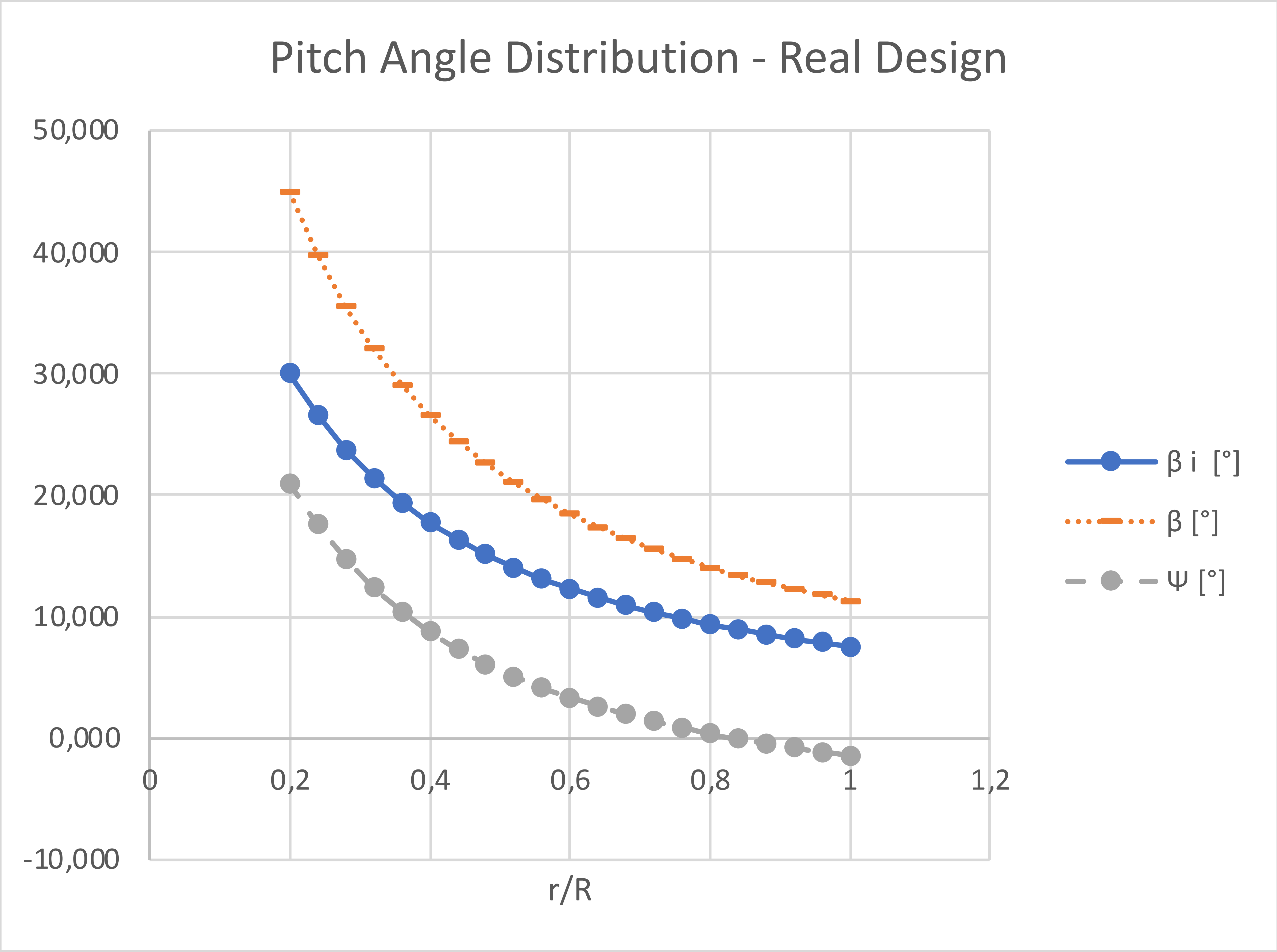
Results (1/3)

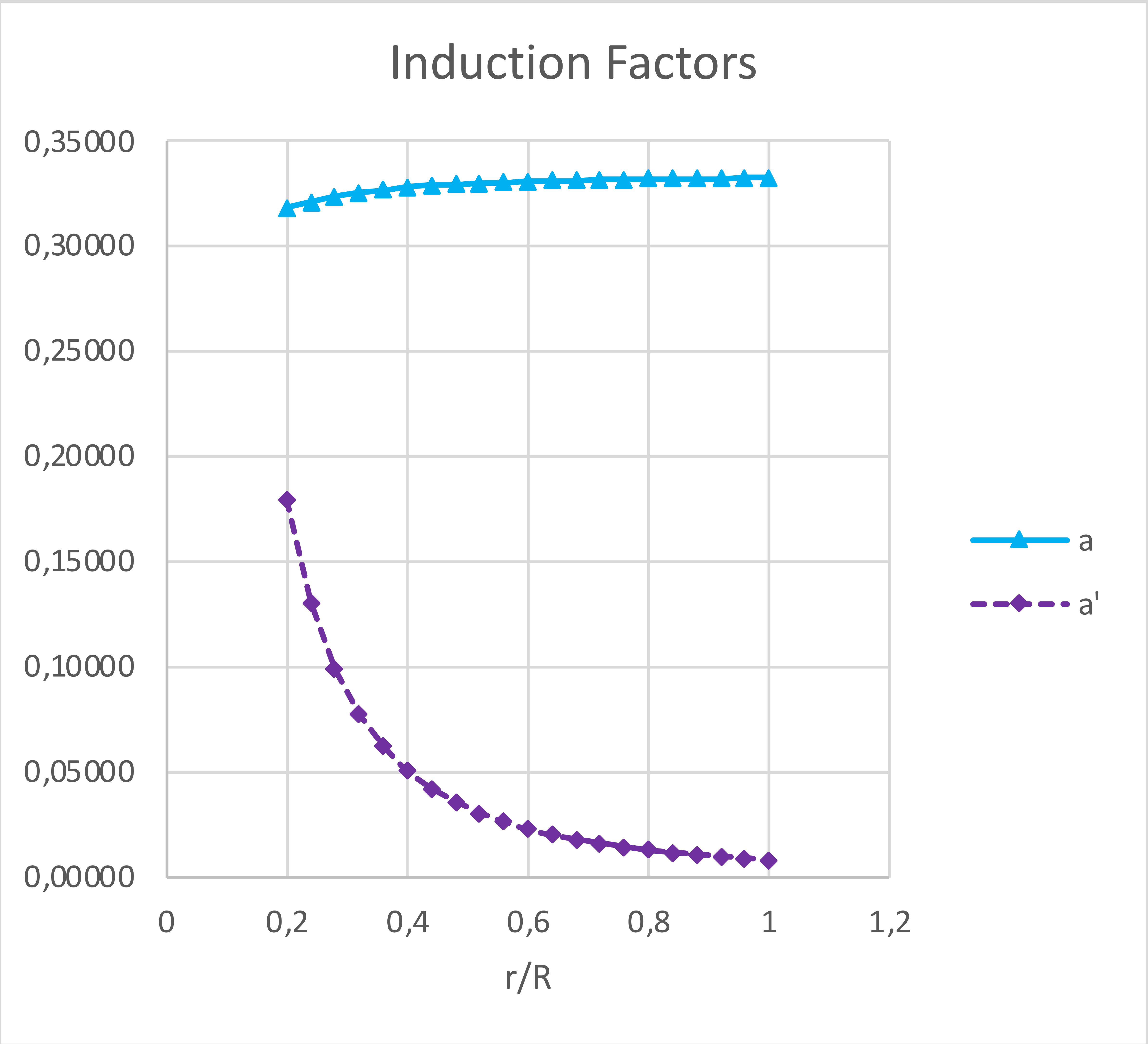
r/R	x	F Glauert	a	a'	β [°]	βi [°]	Ψ [°]	k	c/R
0,200	1,000	3,367	0,26058	0,19014	45,000	34,227	25,227	0,99750	0,15935
0,240	1,200	2,648	0,32090	0,13067	39,806	26,589	17,589	0,99678	0,15026
0,280	1,400	2,118	0,32352	0,09899	35,538	23,734	14,734	0,99580	0,14010
0,320	1,600	1,723	0,32544	0,07737	32,005	21,372	12,372	0,99449	0,13004
0,360	1,800	1,423	0,32686	0,06200	29,055	19,399	10,399	0,99274	0,12060
0,400	2,000	1,191	0,32794	0,05072	26,565	17,735	8,735	0,99042	0,11193
0,440	2,200	1,010	0,32879	0,04221	24,444	16,317	7,317	0,98734	0,10405
0,480	2,400	0,865	0,32945	0,03563	22,620	15,098	6,098	0,98327	0,09690
0,520	2,600	0,749	0,32998	0,03046	21,038	14,041	5,041	0,97787	0,09037
0,560	2,800	0,654	0,33041	0,02631	19,654	13,116	4,116	0,97072	0,08437
0,600	3,000	0,576	0,33076	0,02294	18,435	12,302	3,302	0,96125	0,07880
0,640	3,200	0,511	0,33106	0,02017	17,354	11,580	2,580	0,94872	0,07355
0,680	3,400	0,456	0,33131	0,01787	16,390	10,936	1,936	0,93209	0,06850
0,720	3,600	0,409	0,33152	0,01593	15,524	10,358	1,358	0,91002	0,06355
0,760	3,800	0,369	0,33170	0,01428	14,744	9,837	0,837	0,88065	0,05857
0,800	4,000	0,334	0,33185	0,01287	14,036	9,365	0,365	0,84137	0,05340
0,840	4,200	0,305	0,33198	0,01166	13,392	8,935	-0,065	0,78841	0,04784
0,880	4,400	0,278	0,33210	0,01060	12,804	8,542	-0,458	0,71582	0,04160
0,920	4,600	0,255	0,33220	0,00968	12,265	8,182	-0,818	0,61295	0,03418
0,960	4,800	0,235	0,33229	0,00887	11,768	7,851	-1,149	0,45451	0,02435
1,000	5,000	0,217	0,33237	0,00816	11,310	7,545	-1,455	0,00000	0,00000

Part 2: Real Flow Design

Drag force present, $C_D \neq 0$

Results (2/3)

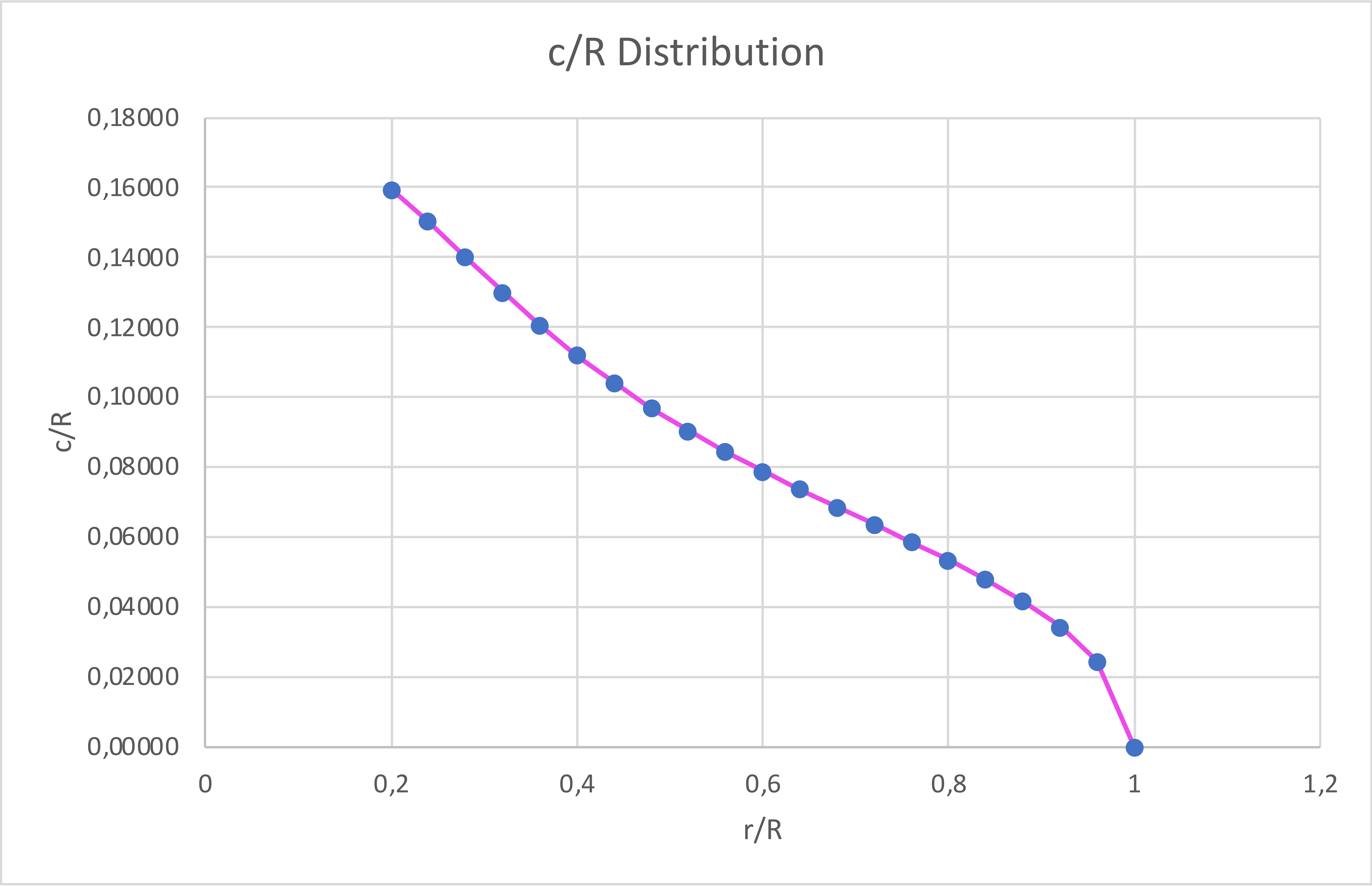


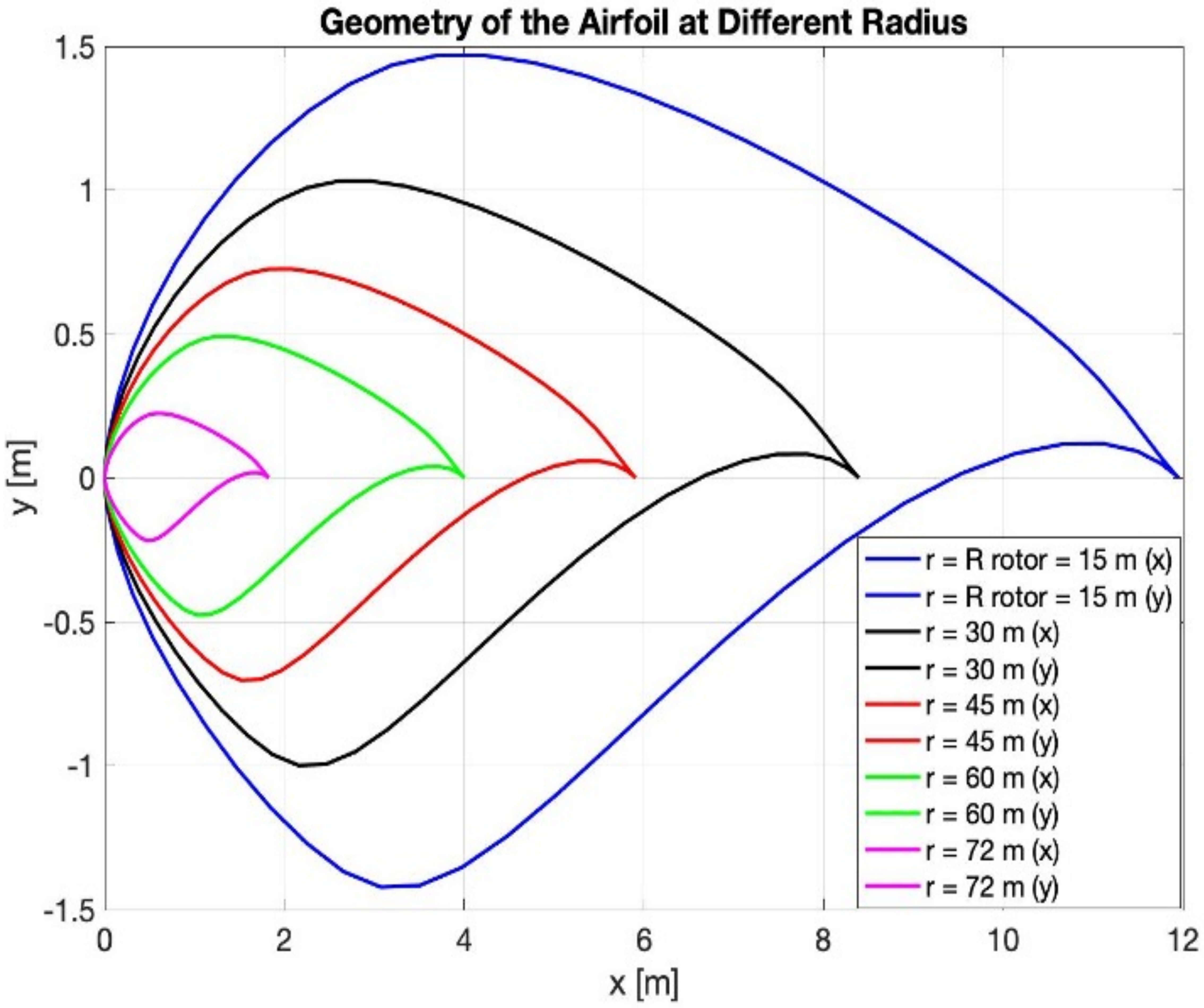


Part 2: Real Flow Design

Drag force present, $C_D \neq 0$

Results (3/3)





Part 3: Real Flow Analysis

Fixed geometry (c/R and ψ)

Equations (1/2)

- Angle of attack

$$\alpha = \beta_i - \psi$$

- Induction factors

$$\frac{a}{1-a} = \frac{F cos\beta_i}{8\pi k sin^2\beta_i}(1 + \varepsilon tan\beta_i)$$

$$\frac{a'}{1-a'} = \frac{F}{8\pi k cos\beta_i}(1 + \varepsilon cot\beta_i)$$

- Lift and drag coefficients

$$C_L = 4.824 \times 10^{-6}\alpha^4 - 0.0002405\alpha^3 - 0.001315\alpha^2 + 0.1301\alpha + 0.4436$$

$$C_D = -5.243 \times 10^{-8}\alpha^5 + 2.214 \times 10^{-6}\alpha^4 + 2.11 \times 10^{-6}\alpha^3 - 0.0001815\alpha^2 + 0.0002379\alpha + 0.01234$$

Part 3: Real Flow Analysis

Fixed geometry (c/R and ψ)

Equations (2/2)

- Power coefficient

$$C_P = \frac{8}{TSR^2}\int_0^{TSR} (1-a)a'x^3dx$$

- Power

$$P = C_p\frac{1}{2}\rho U^3 A$$

- Thrust coefficient

$$T = \int_0^{R} 4\pi r\rho U^2 ka(1-a)dr$$

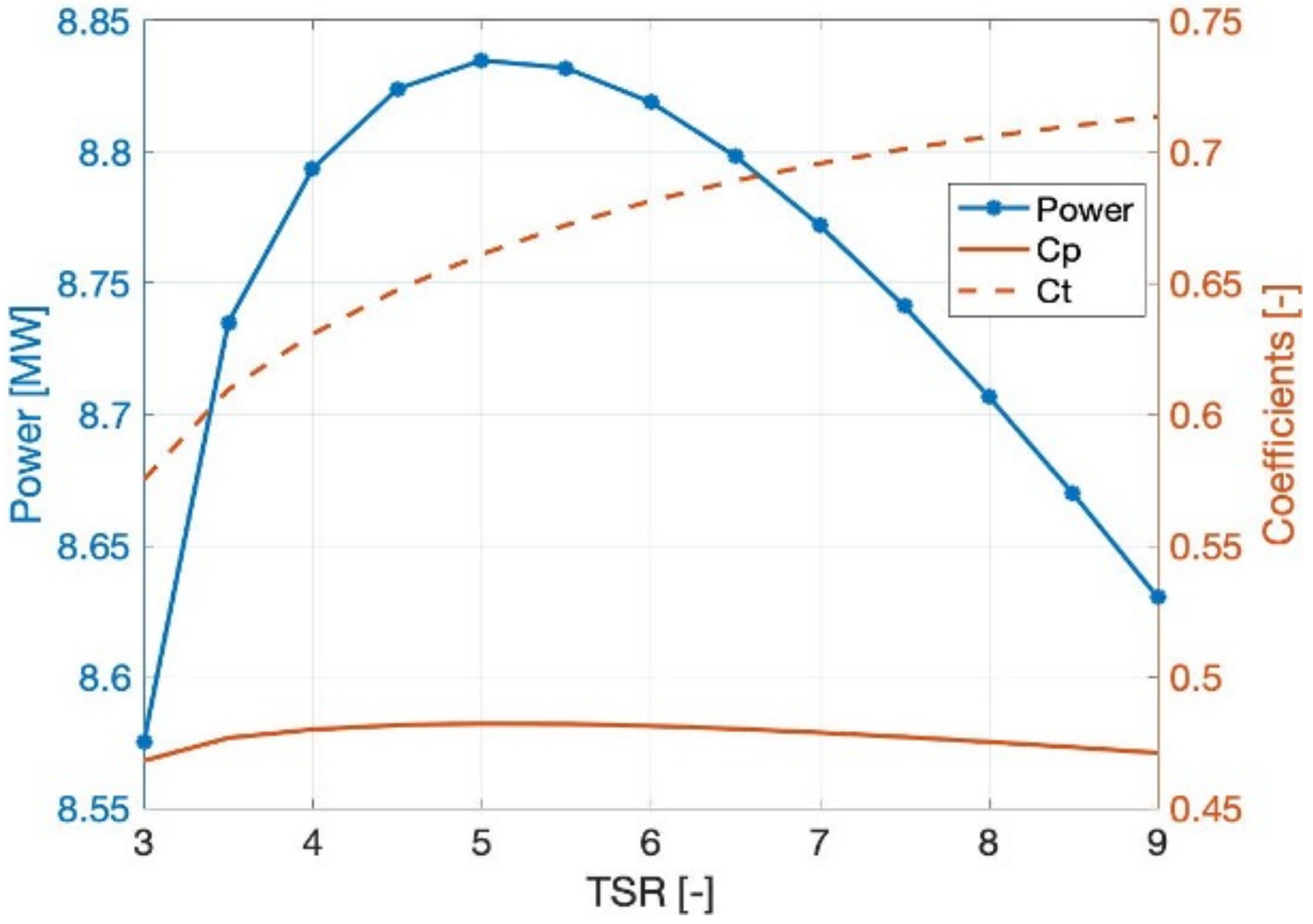
$$C_T = \frac{T}{\frac{1}{2}\rho U^2 A}$$

Part 3: Real Flow Analysis

Fixed geometry (c/R and ψ)

Results (1/1)

C_P	0,482	-
Power	8,835	MW
C_T	0,661	-



Conclusion

- The inflow angle β_i slightly decreases in the second point with respect to the first one
- The chord also slightly decreases near the rotor and goes to zero at the tip in the second point
- The real flow method is more accurate that the Glauert approximation even if it is more difficult to implement
- The design power is equal to about 8.83 MW with a C_P equal to 0.48
- Varying the TSR the power output decreases, this can be a form of regulation of the turbine