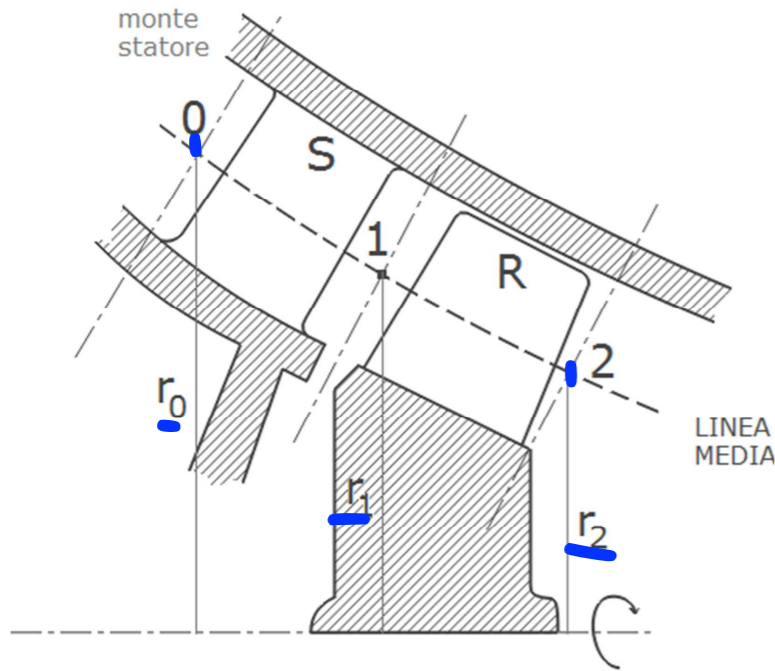


# Lezione 19\_20

# Calcolo delle proprietà termodinamiche nell'attraversamento della turbina

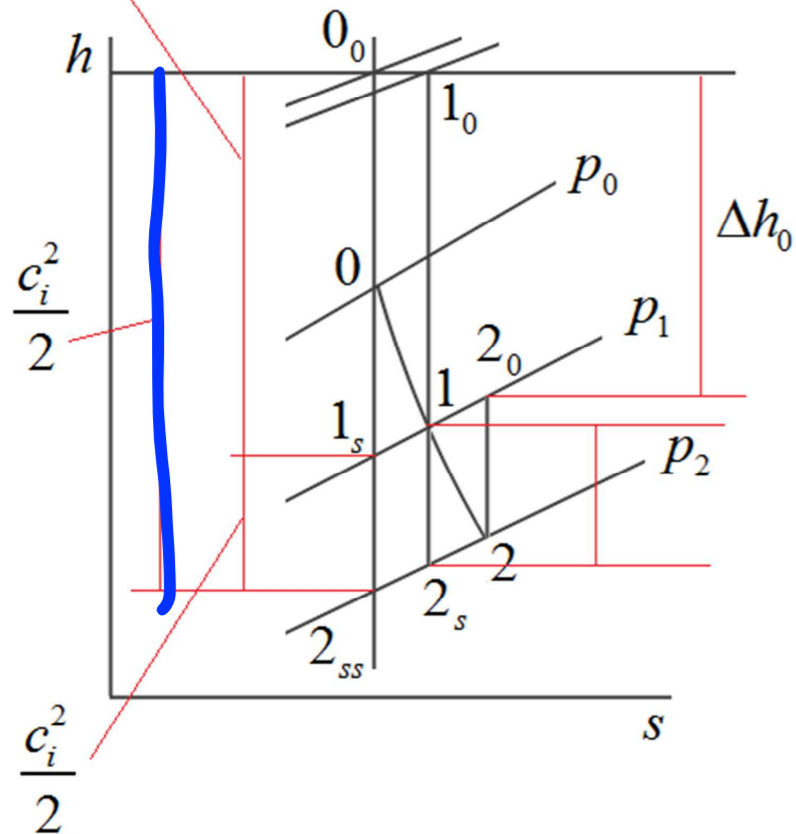


$$M_u = \frac{u_1}{a_{0_0}} \quad \text{def. Mach periferico}$$

$$a_{0_0} = \sqrt{kRT_{0_0}} = \sqrt{\frac{c_p}{c_v} (c_p - c_v) T_{0_0}} = \sqrt{h_{0_0} (k - 1)}$$

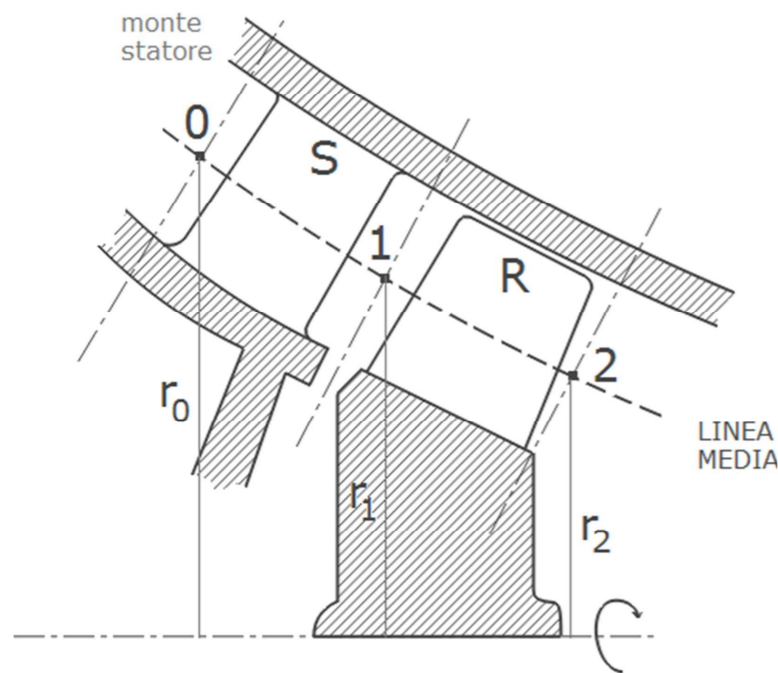
$(1 - R^*) \frac{c_i^2}{2}$  ricordiamo:

$$\psi = \frac{h_{0_0} - h_{2_{ss}}}{\frac{u_1^2}{2}} = \frac{c_i^2}{u_1^2} = \frac{\Delta h_{is_{ts}}}{\frac{u_1^2}{2}}$$

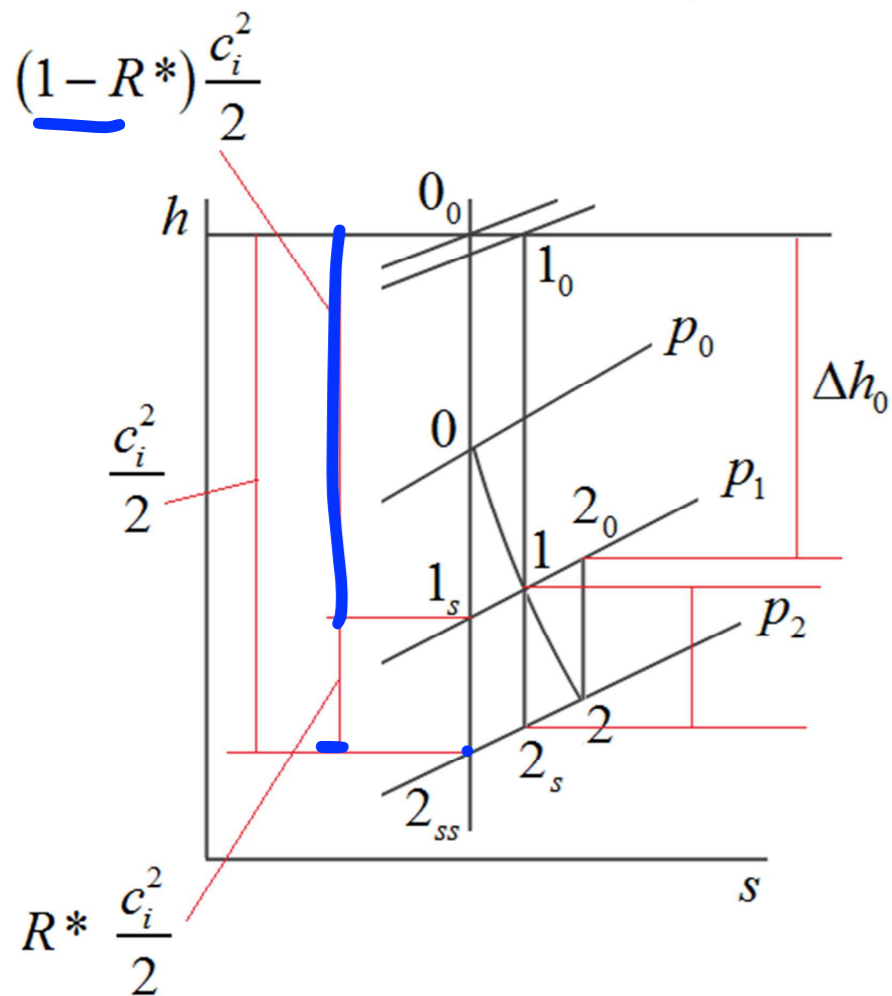


$$\left[ \frac{c_i^2}{2} = \psi \frac{u_1^2}{2} \frac{a_{0_0}^2}{a_{0_0}^2} = \frac{\psi}{2} M_u^2 (k - 1) h_{0_0} \right]$$

# Calcolo delle proprietà termodinamiche nell'attraversamento della turbina

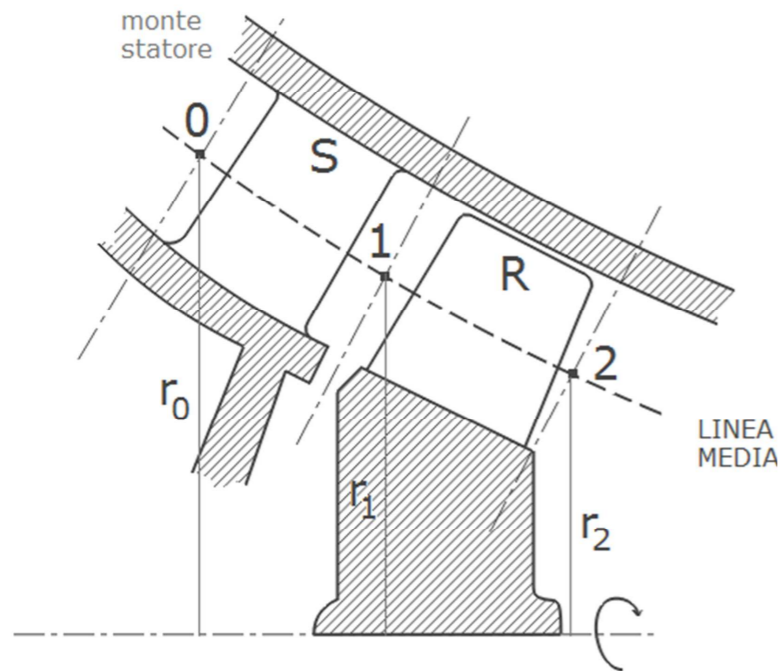


$$h_{1s} = h_{0_0} - (1 - R^*) \frac{c_i^2}{2} = h_{0_0} \left[ 1 - (1 - R^*) \frac{k-1}{2} \psi M_u^2 \right]$$



$$h_{2_{ss}} = h_{0_0} - \frac{c_i^2}{2} = h_{0_0} \left[ 1 - \frac{k-1}{2} \psi M_u^2 \right]$$

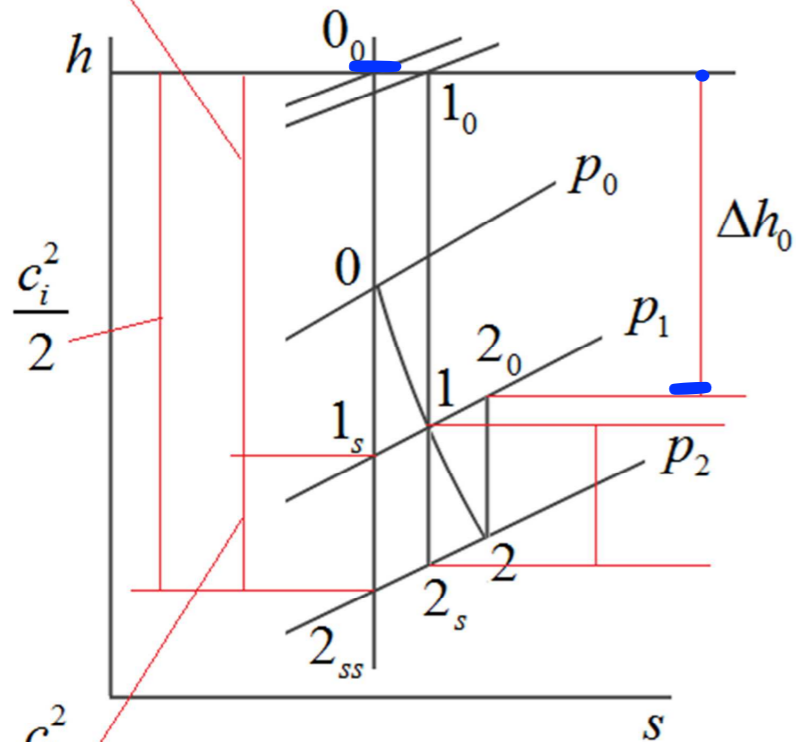
# Calcolo delle proprietà termodinamiche nell'attraversamento della turbina



$$\frac{c_1^2}{2} = \eta_s \frac{c_i^2}{2} (1 - R^*)$$

$$h_1 = h_{0_0} - \frac{c_1^2}{2} = h_{0_0} \left[ 1 - \underbrace{(1 - R^*)}_{\text{blue}} \frac{k-1}{2} \underbrace{\eta_s \psi M_u^2}_{\text{blue}} \right]$$

$$(1 - R^*) \frac{c_i^2}{2}$$



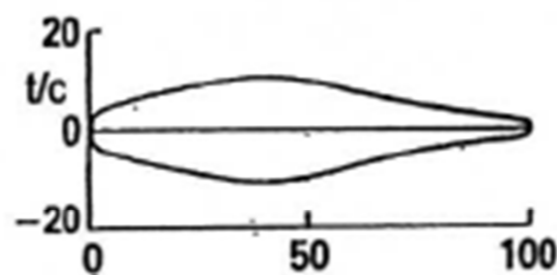
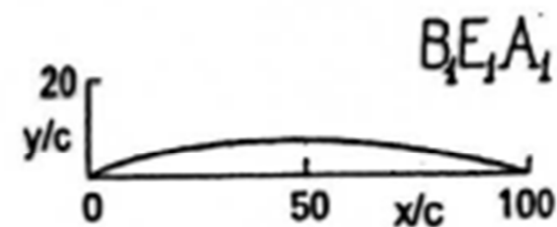
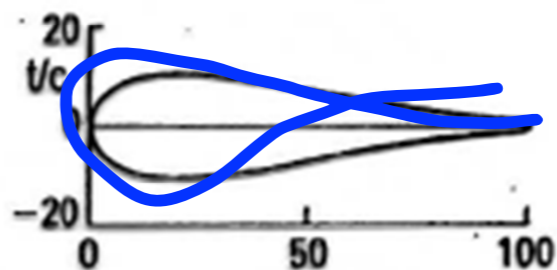
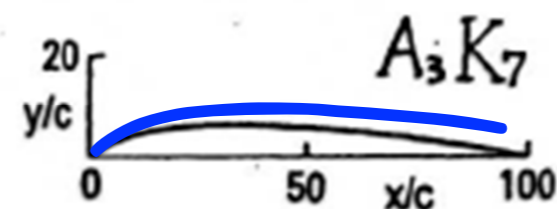
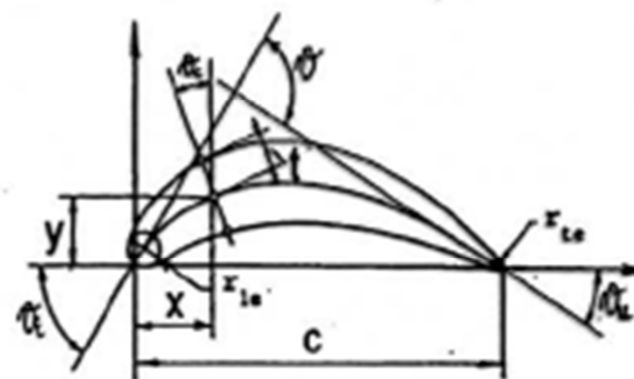
$$h_2 = h_{0_0} - \Delta h_0 - \frac{c_2^2}{2} = h_{0_0} \left[ 1 - \left( \underbrace{\eta_{T,S}}_{\text{blue}} + \frac{C_2^2}{\psi} \right) \frac{k-1}{2} \underbrace{\psi M_u^2}_{\text{blue}} \right]$$

$$R^* \frac{c_i^2}{2}$$

# Schiere di pale per turbine assiali

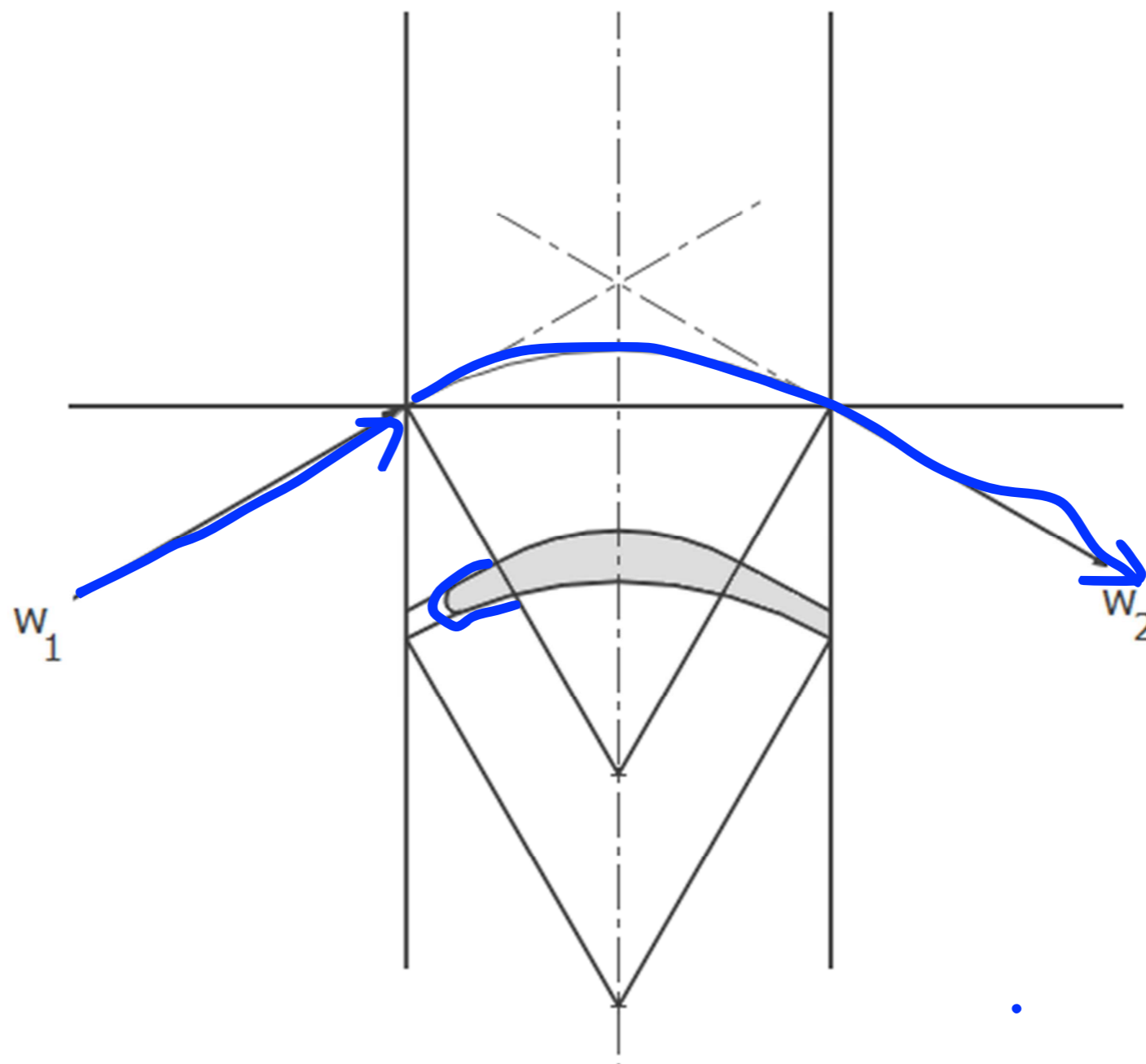
Profili subsonici  
(bassa deflessione)

$A_3K_7$			$B_1E_1A_1$		
x/c [%]	y/c [%]	t/c [%]	x/c [%]	y/c [%]	t/c [%]
0	0	0	0	0	0
1,25	0,836	3,469	1,25	0,718	2,583
2,5	1,428	4,972	2,5	1,253	3,282
5,0	2,359	6,918	5,0	2,128	4,041
10	3,689	9,007	10	3,480	5,007
15	4,597	9,827	15	4,506	5,592
20	5,217	10,00	20	5,291	6,995
25	5,623	9,899	25	5,862	8,063
30	5,852	9,613	30	6,261	9,025
35	5,936	9,106	35	6,514	9,727
40	5,897	8,594	40	6,642	10,00
45	5,753	7,913	45	6,651	9,725
50	5,516	7,152	50	6,652	9,009
55	5,200	6,339	55	6,342	8,016
60	4,814	5,500	60	6,016	6,908
65	4,367	4,661	65	5,551	5,848
70	3,870	3,848	70	4,983	5,000
75	3,328	3,087	75	4,332	4,312
80	2,746	2,406	80	3,680	3,624
85	2,133	1,830	85	2,824	2,936
90	1,485	1,387	90	1,953	2,248
95	0,801	1,101	95	0,948	1,560
100	0	0	100	0	0
$\frac{x_{1a}}{c} = 0,04407$ $\frac{x_{2a}}{c} = 0,01$			$\frac{x_{1a}}{c} = 0,033$ $\frac{x_{2a}}{c} = 0,01$		
$\text{tg } \vartheta_i = 0,8574, \vartheta_i = 40,52^\circ$			$\text{tg } \vartheta_i = 0,5657, \vartheta_i = 29,5^\circ$		
$\text{tg } \vartheta_u = 0,1602, \vartheta_u = 9,1^\circ$			$\text{tg } \vartheta_u = 0,2017, \vartheta_u = 11,4^\circ$		



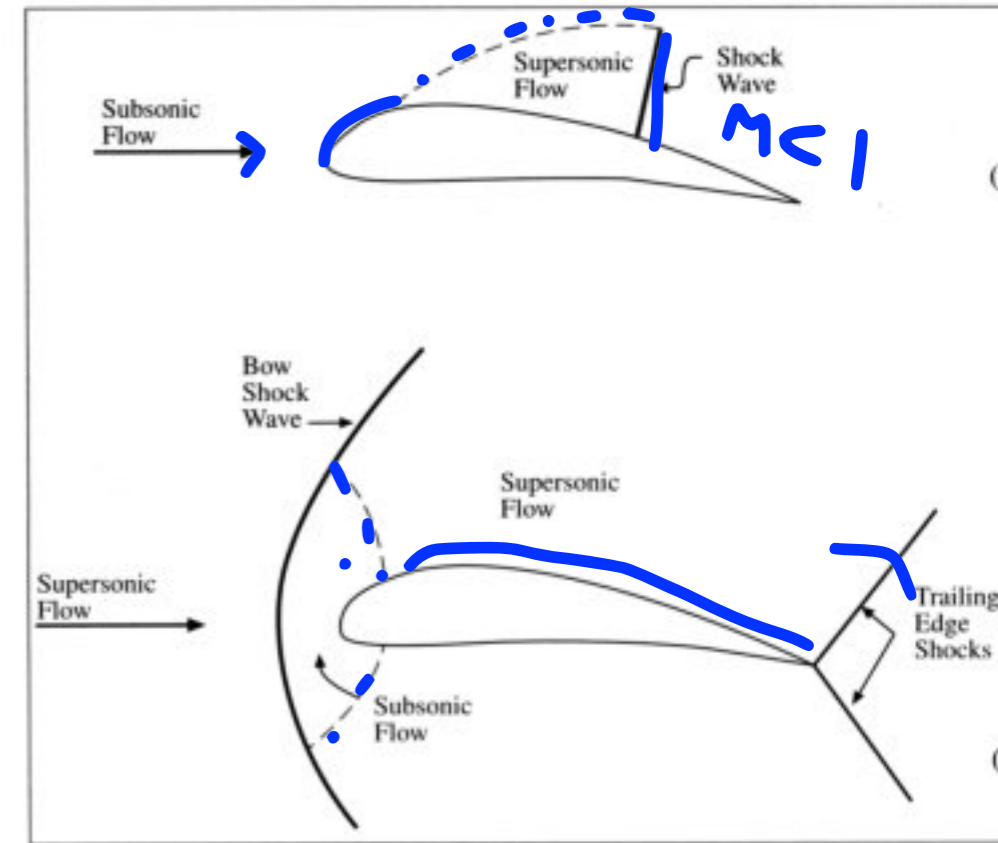
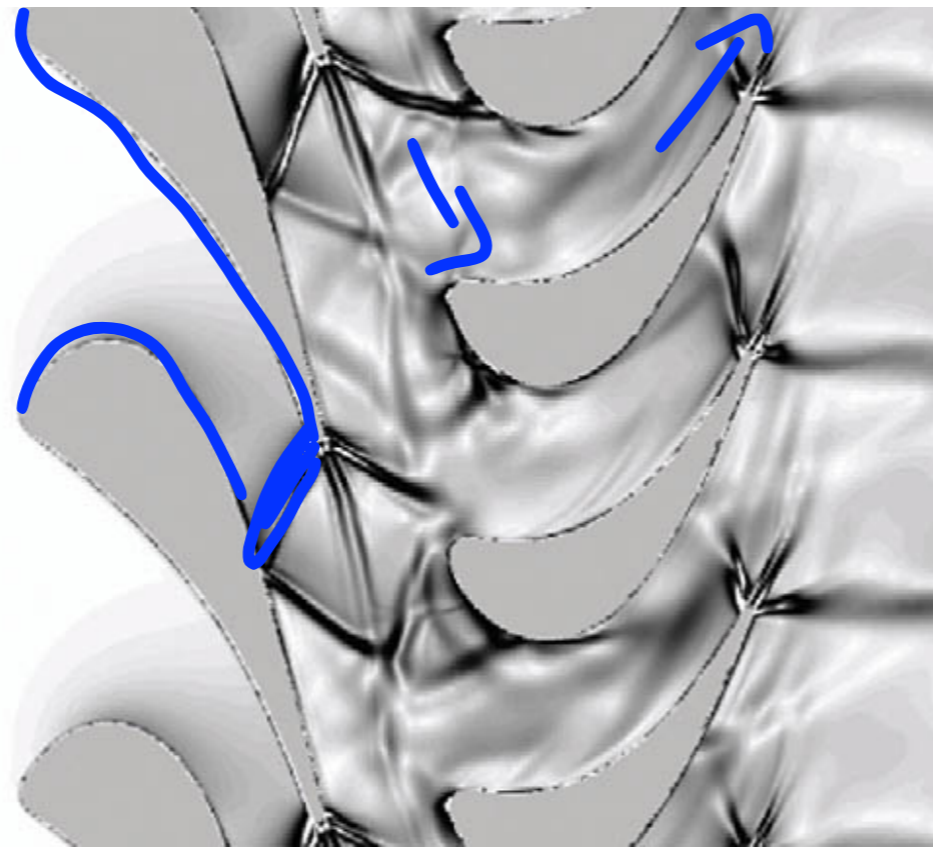
# Schiere di pale per turbine assiali

Profili  
subsonici  
(alta  
deflessione)

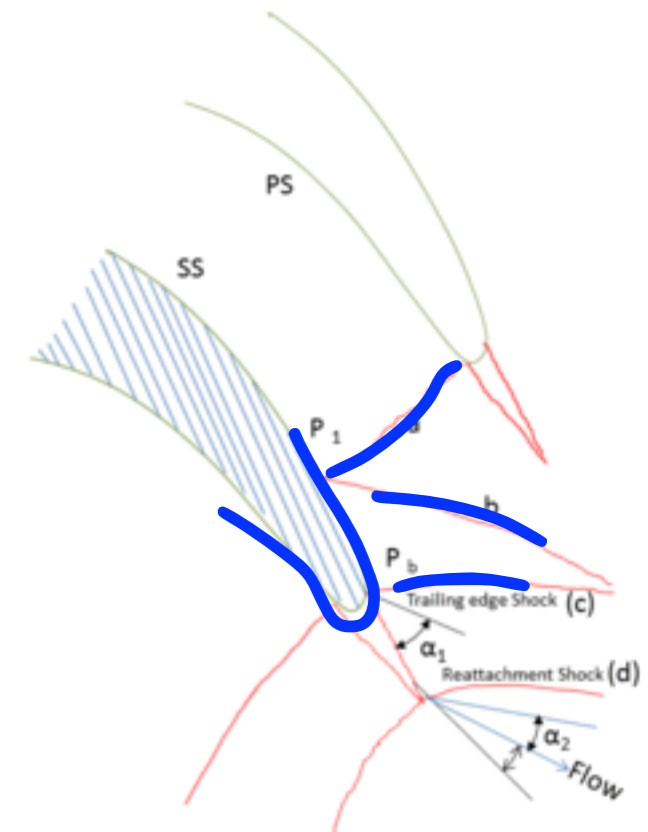
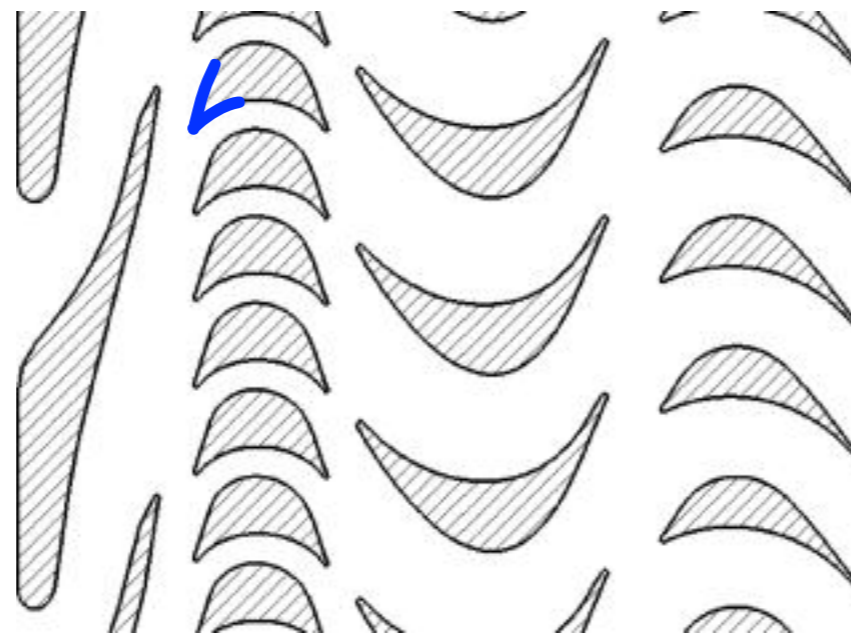


# Schiere di pale per turbine assiali

Ugelli supersonici

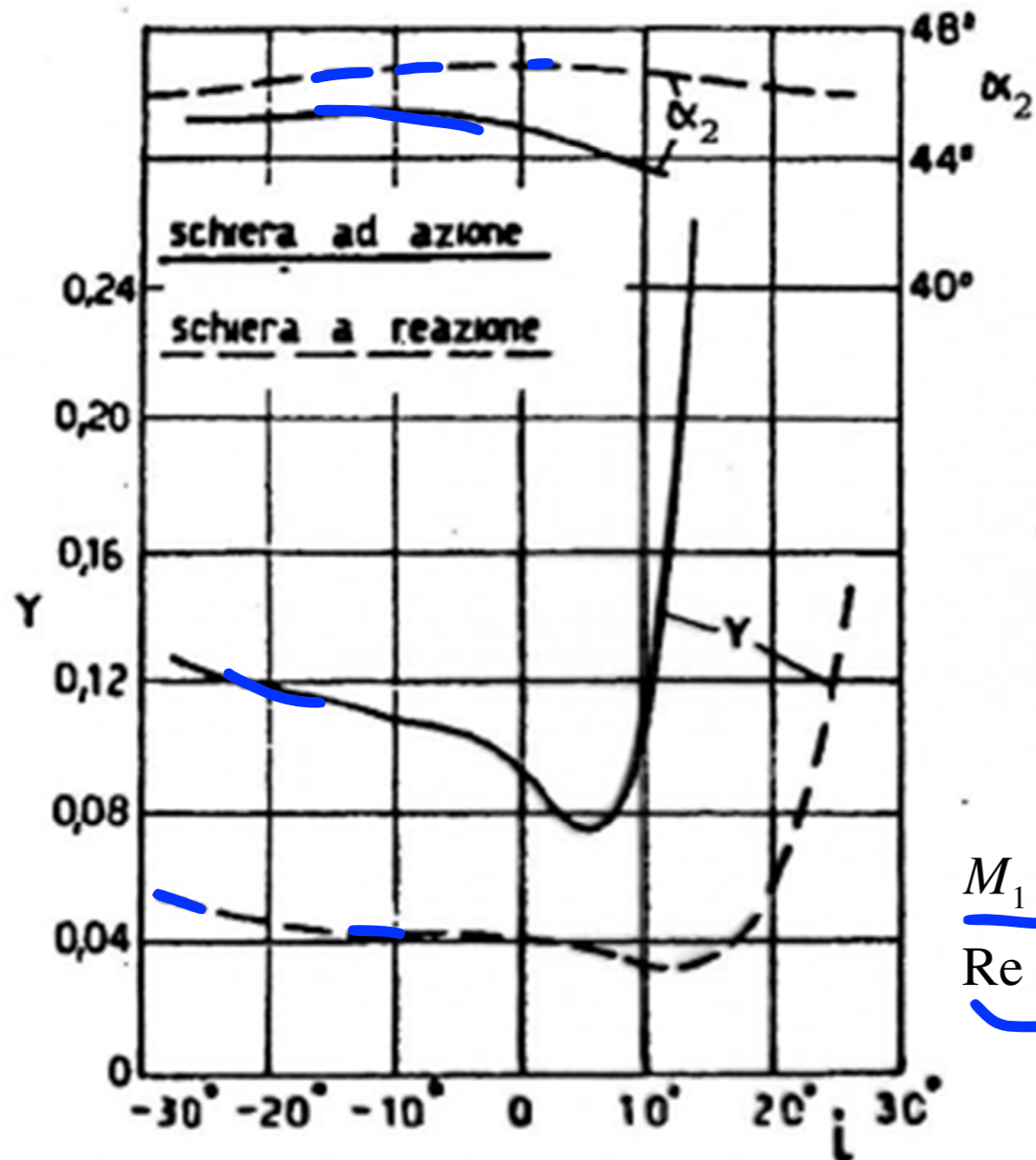


pale supersoniche  
(spigolo in ingresso)



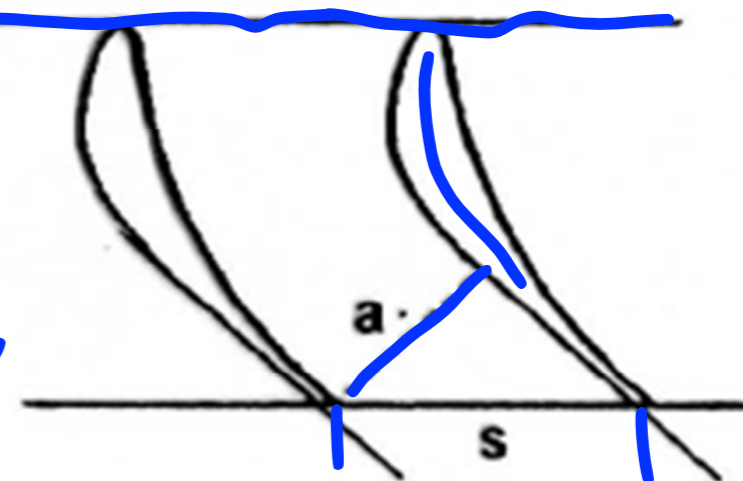
# prestazioni delle schiere di turbina

definiti i triangoli di velocità si cerca:  $\underline{y}, \underline{\alpha_2} = f(\alpha_1)$   
 (trascurando influenza di M e Re)



	azione	reazione
$\alpha_1^*$	45.5°	18.9°
$\alpha_2^*$	-45.8°	-47.1°
s/c	0.625	0.580
t/c	0.22	0.15
$\arccos(a/s)$	50°	50°

$M_1 = 0,5$   
 $Re = 1,5 \cdot 10^5$

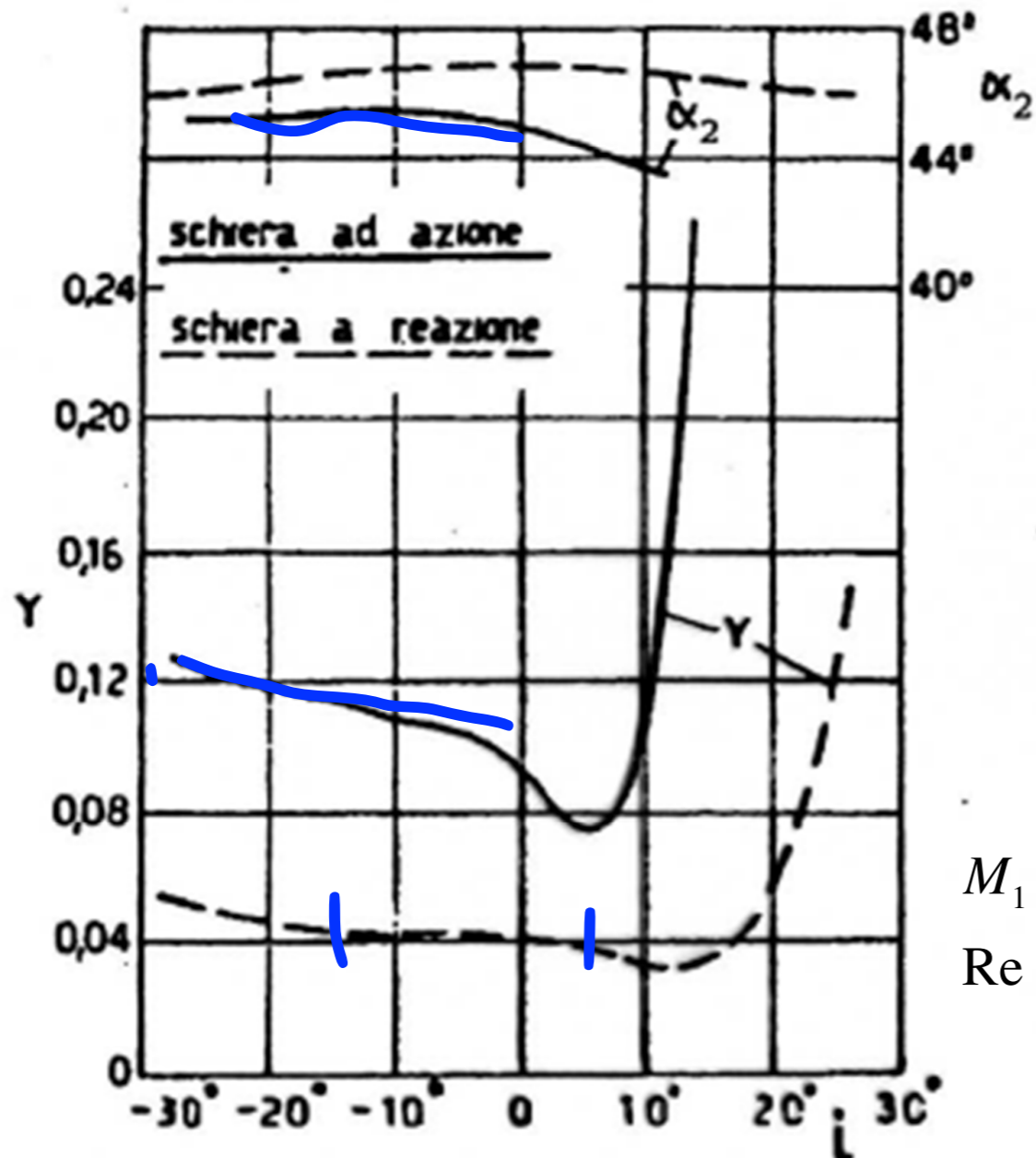




# prestazioni delle schiere di turbina

angolo di uscita geometrico:  $\arccos \frac{a}{s}$

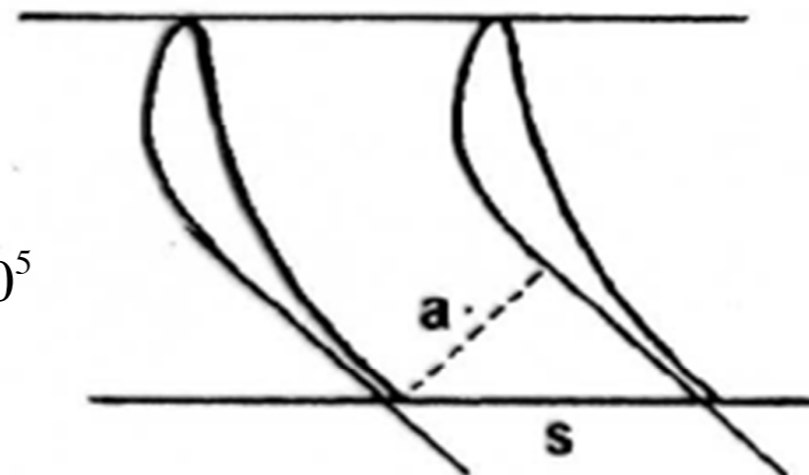
- $\alpha_2$  poco variabile al variare dell'incidenza
- coeff. perdita quasi costante al variare dell'incidenza



	azione	reazione
$\alpha_1^*$	45.5°	18.9°
$\alpha_2^*$	-45.8°	-47.1°
s/c	0.625	0.580
t/c	0.22	0.15
arcos(a/s)	50°	50°

$$M_1 = 0,5$$

$$Re = 1,5 \cdot 10^5$$



# prestazioni delle schiere di turbina

- riferiamoci a una schiera statorica (0 1)
- angolo di uscita geometrico  $\alpha_1 = \arccos \frac{a}{s}$

$$\cos \alpha_1 = \frac{1}{k} \cos \alpha_1^*$$

k puo' essere stimato con diverse correlazioni:

$$k = 1 - 10750 \left( \frac{t}{s} \right)^{3,3} \left( \frac{a}{s} \right) \quad \text{Vaura}$$

# perdite delle schiere di turbina

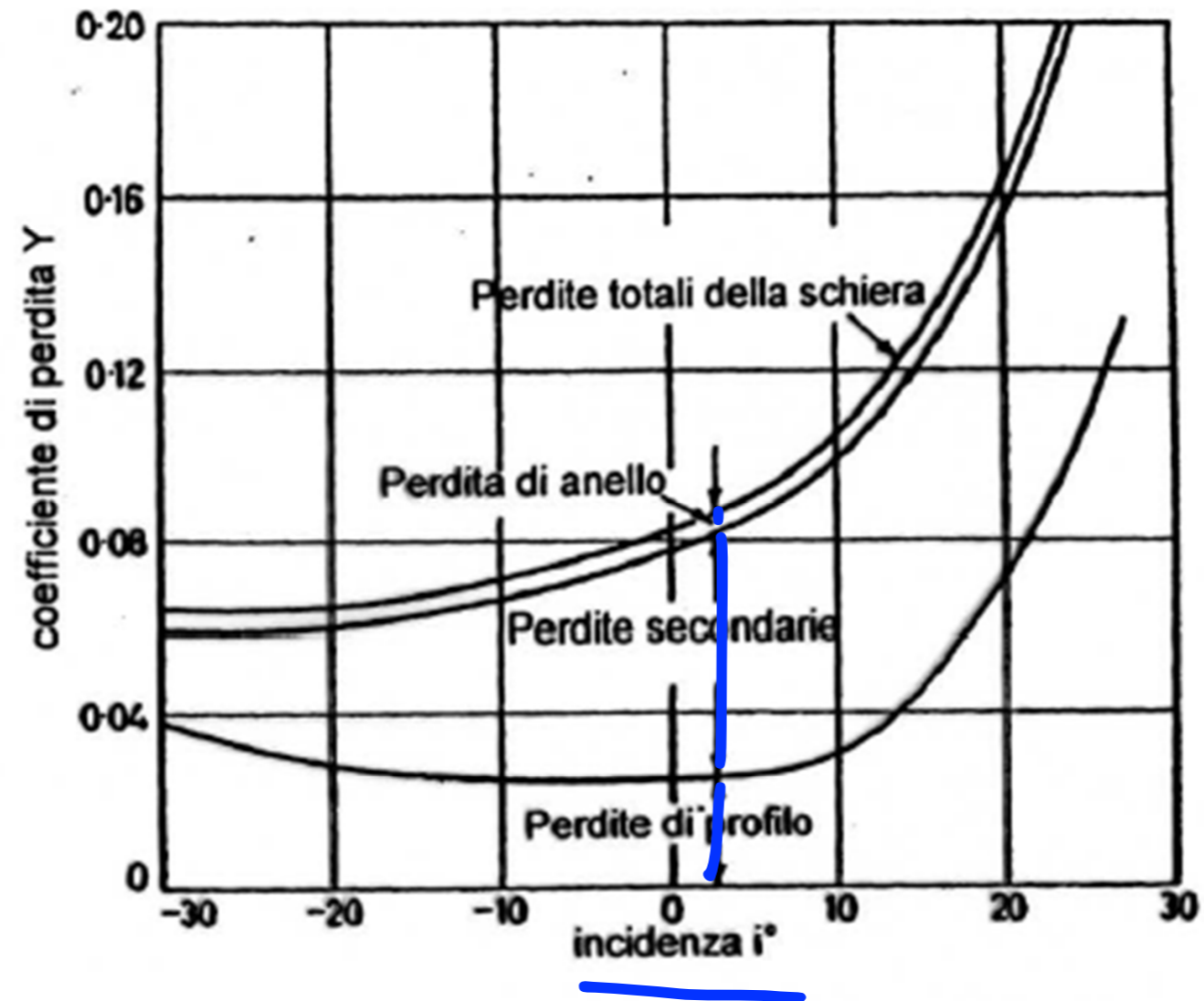




Figura 9.18: Perdite di pressione totale in una schiera di turbina in funzione dell'incidenza.

# perdite delle schiere di turbina

## Correlazione di Soderberg

perdita di energia cinetica a valle della schiera

$$\xi = \xi_1 = \frac{|h_1 - h_{1s}|}{\frac{1}{2}c_1^2} \quad \text{statore}$$


$$\xi = \xi_2 = \frac{|h_2 - h_{2s}|}{\frac{1}{2}w_2^2} \quad \text{rotore}$$


# perdite delle schiere di turbina

## Correlazione di Soderberg

Coefficienti funzioni di:

- deflessione cinematica

$\Delta\alpha$  (statore) e  $\Delta\beta$  (rotore)

- Numero di Re

$$\text{Re} = \frac{D_i c_1}{\nu}$$

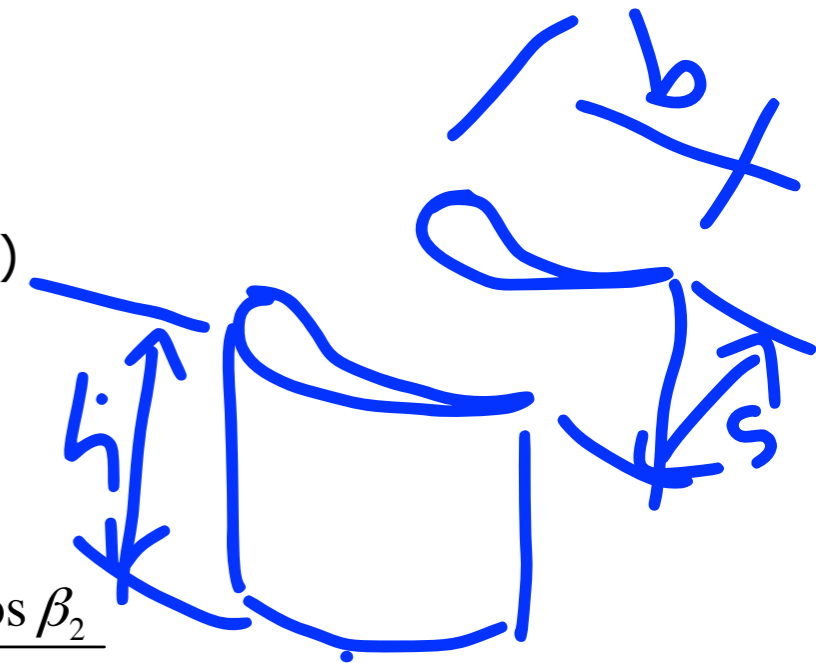
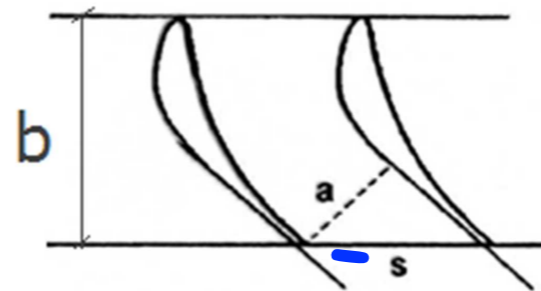
- Diametro idraulico

$$D_i = \frac{2hs \cos \alpha_1}{h + s \cos \alpha_1} \quad D_i = \frac{2hs \cos \beta_2}{h + s \cos \beta_2}$$

- h altezza della pala

- allungamento della pala h/b

-  $t/c$



# perdite delle schiere di turbina

Correlazione di Soderberg

$$\xi = \left( \frac{10^5}{\text{Re}} \right)^{0,25} \left[ (1 + \xi^*) \left( 0,975 + 0,075 \frac{h}{b} \right) - 1 \right] \quad \text{statore}$$

$$\xi = \left( \frac{10^5}{\text{Re}} \right)^{0,25} \left[ (1 + \xi^*) \left( 0,993 + 0,021 \frac{h}{b} \right) - 1 \right] \quad \text{rotore}$$

# perdite delle schiere di turbina

## Correlazione di Soderberg

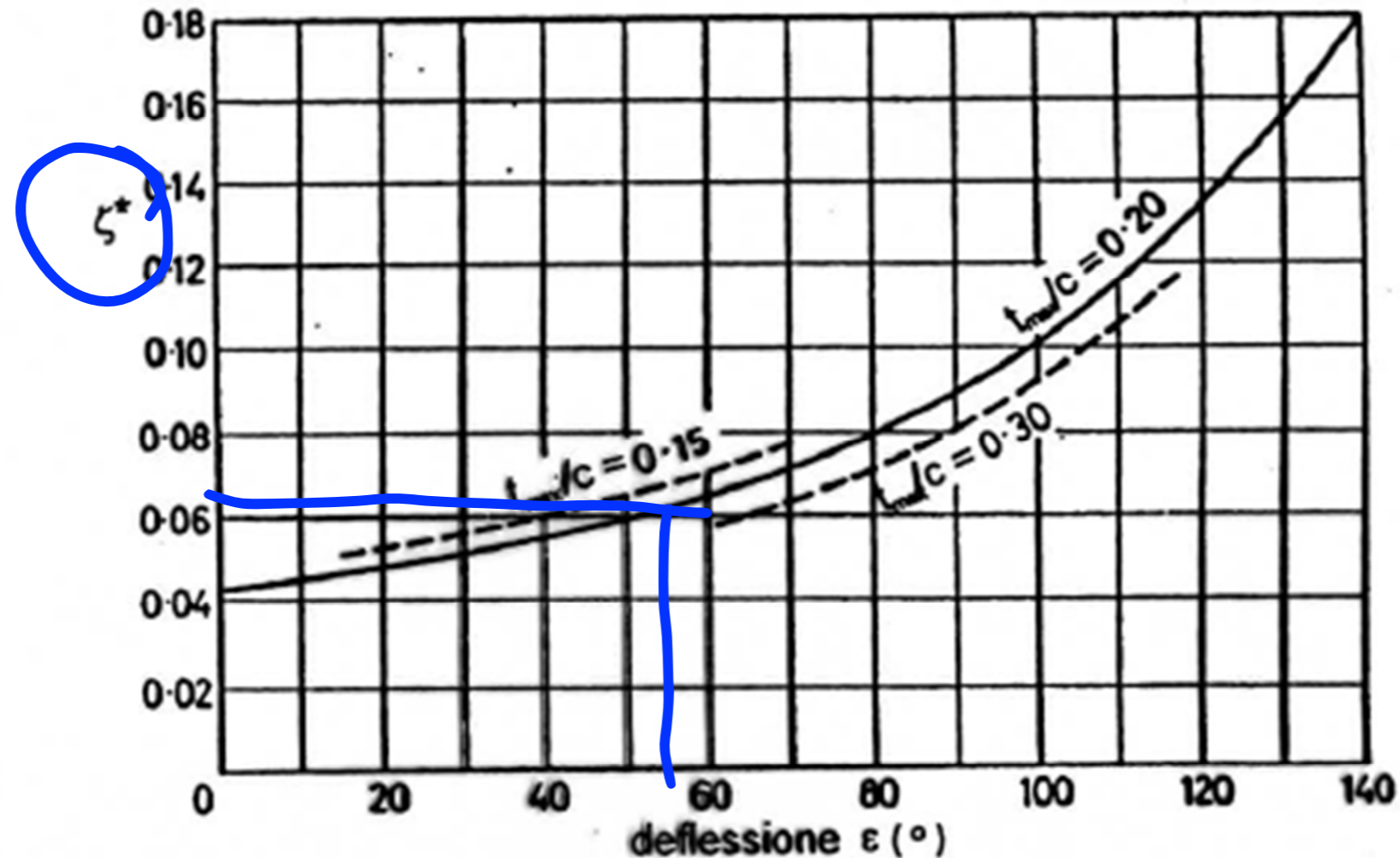


Figura 9.19: Coefficiente di perdita base secondo Soderberg in funzione della deflessione cinematica ( $Re = 10^5$ ,  $h/b = 3$ ).

# perdite delle schiere di turbina

Correlazione di Ainley-Mathieson (perdite di profilo)

$$Y_P = \frac{p_{0_0} - p_{1_0}}{p_{1_0} - p_1}$$

- $Re = 2 \cdot 10^5$  (basato sulla corda)
- $M_1 < 0,6$
- $t_{\max}/c = 0,2$
- $t/s = 0,02$
- Condizioni nominali (angolo di incidenza nullo)

$$Y_P = \left[ Y_P^* + m_\alpha^2 (Y_P^{**} - Y_P^*) \right] \left( \frac{t_{\max}}{c} \right)^{m_\alpha}$$

$$m_\alpha = -\frac{\alpha_0}{\alpha_1}$$

$$Y_P^* \rightarrow \begin{cases} \alpha_0 = 0 \\ R = 0 \\ m_\alpha = 0 \end{cases}$$

$$Y_P^{**} \rightarrow \begin{cases} \alpha_1 = -\alpha_0 \\ R = 0.5 \\ m_\alpha = 1 \end{cases}$$

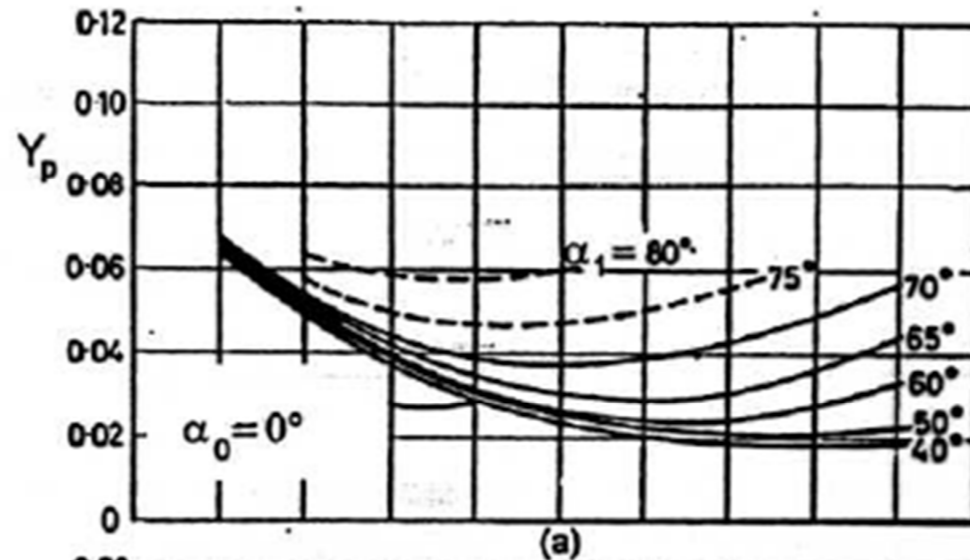
$$0,15 \leq \frac{t_{\max}}{c} \leq 0,25$$



# perdite delle schiere di turbina

Correlazione di Ainley-Mathieson (perdite di profilo)

$Y_p^*$



$Y_p^{**}$

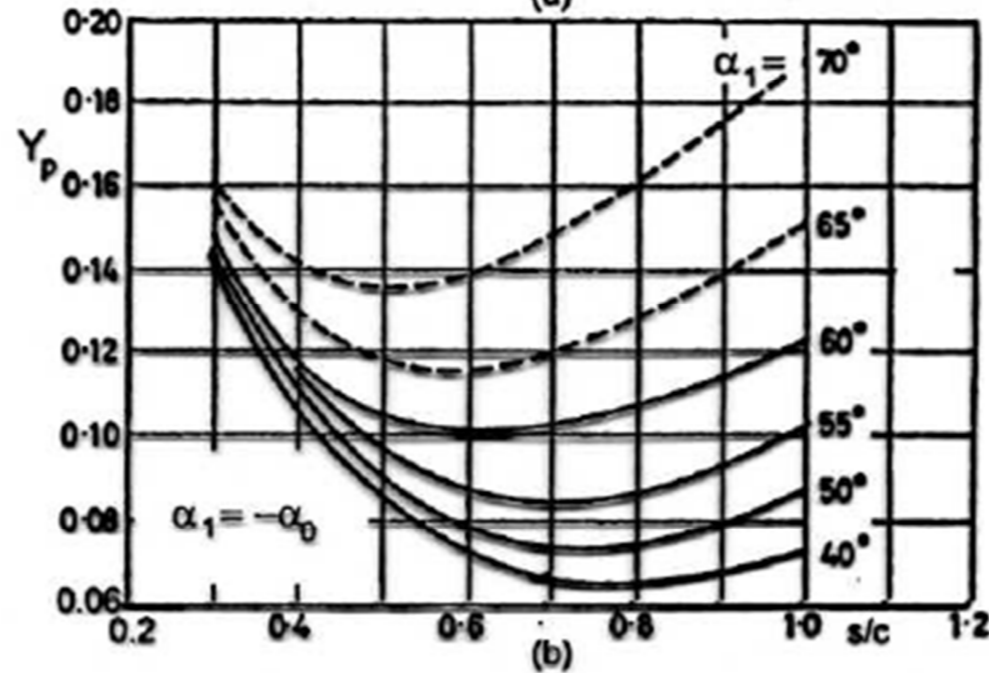


Figura 9.21: Perdite di profilo secondo Ainley e Mathieson per ugelli (a) e pale ad azione (b), in condizioni standard, in funzione di  $s/c$  e dell'angolo a valle.

# perdite delle schiere di turbina

Correlazione di Ainley-Mathieson (perdite di profilo)

$$Y_P = Y_{P,0.02} \left[ 1 + 7 \left( \frac{t}{s} - 0,02 \right) \right]$$

correzione per diverso spessore in uscita

$$Y_P = Y_{P,2 \times 10^5} \left( \frac{2 \times 10^5}{\text{Re}} \right)^{0,2}$$

correzione per diverso Re

# perdite delle schiere di turbina

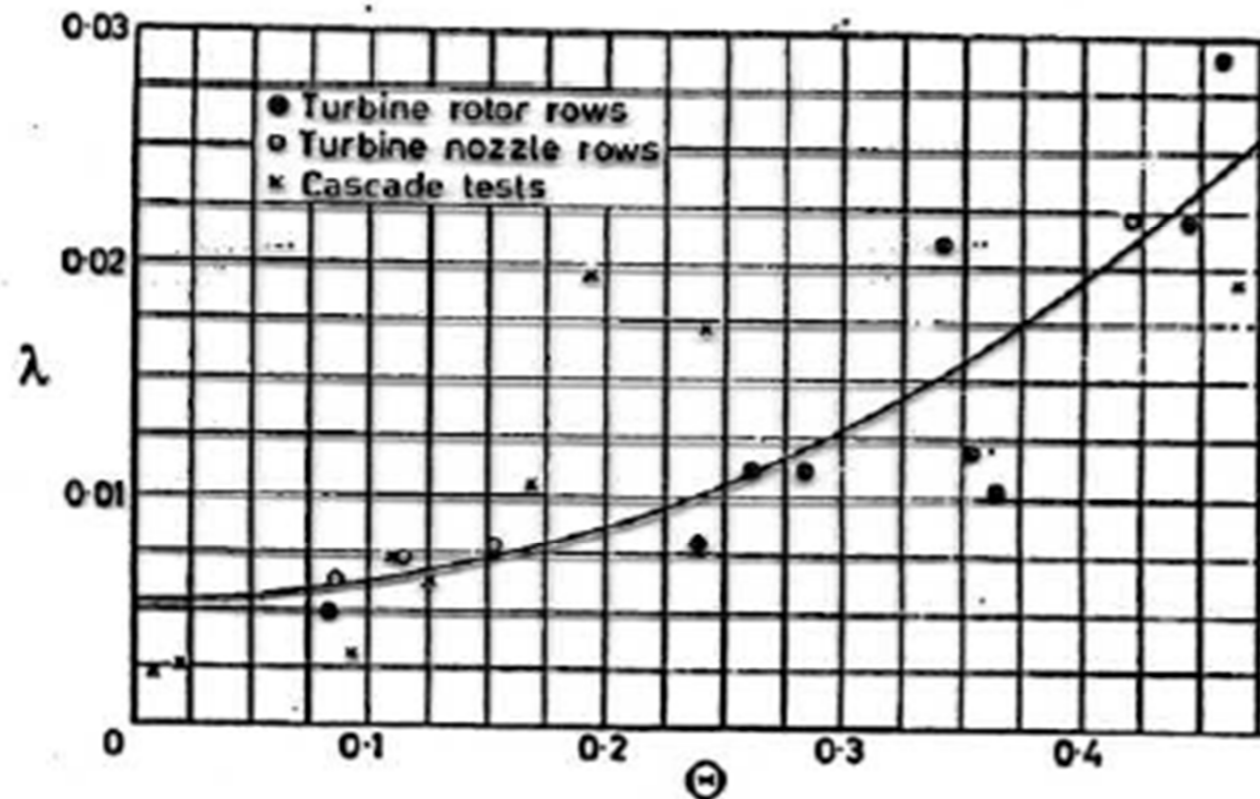
perdite secondarie e giochi

$$Y_S + Y_G = \left( \lambda + B \frac{\delta}{k} \right) \left( \frac{c_L}{\frac{s}{c}} \right)^2 \frac{\cos^2 \alpha_1}{\cos^3 \alpha_\infty}$$

- $B = 0,5$  pale "libere"
- $B = 0,25$  pale "cerchiate"
- $h$  è l'altezza della pala
- $\delta$  è il gioco radiale
- $\lambda$  è un coefficiente sperimentale



$$\theta = \frac{\left( \frac{A_1}{A_0} \right)^2}{\left( 1 + \frac{D_i}{D_e} \right)}$$



# condizioni fuori progetto

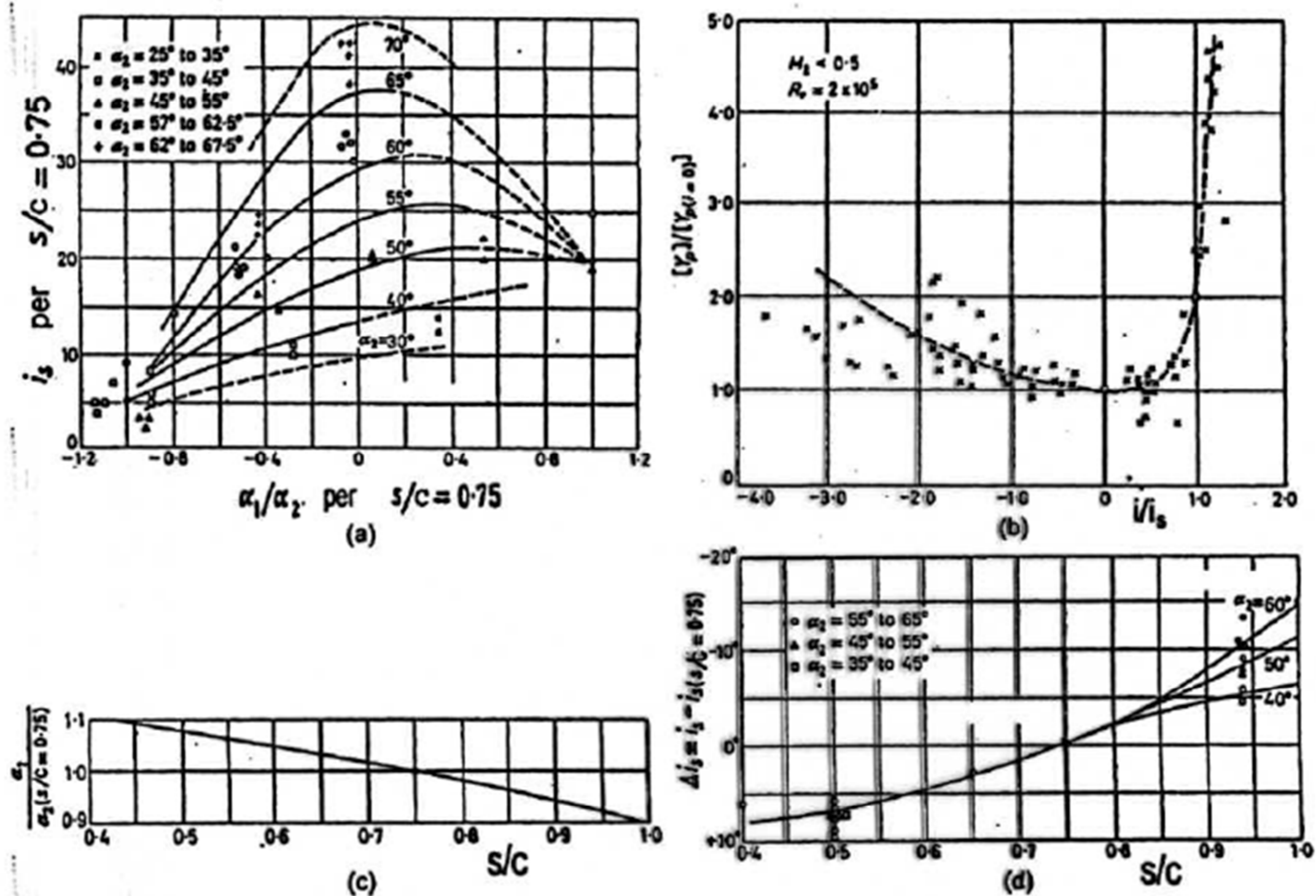
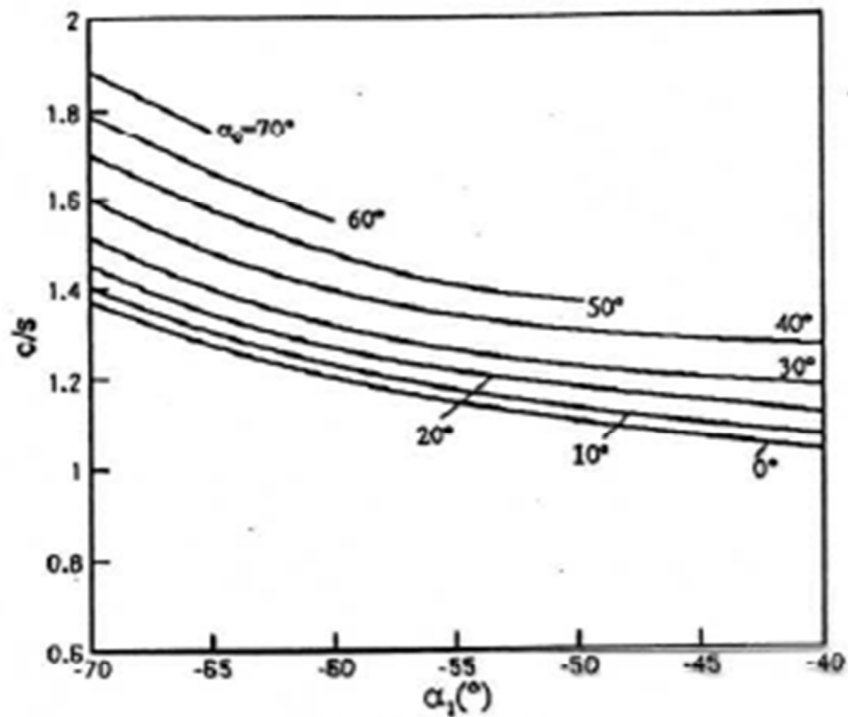
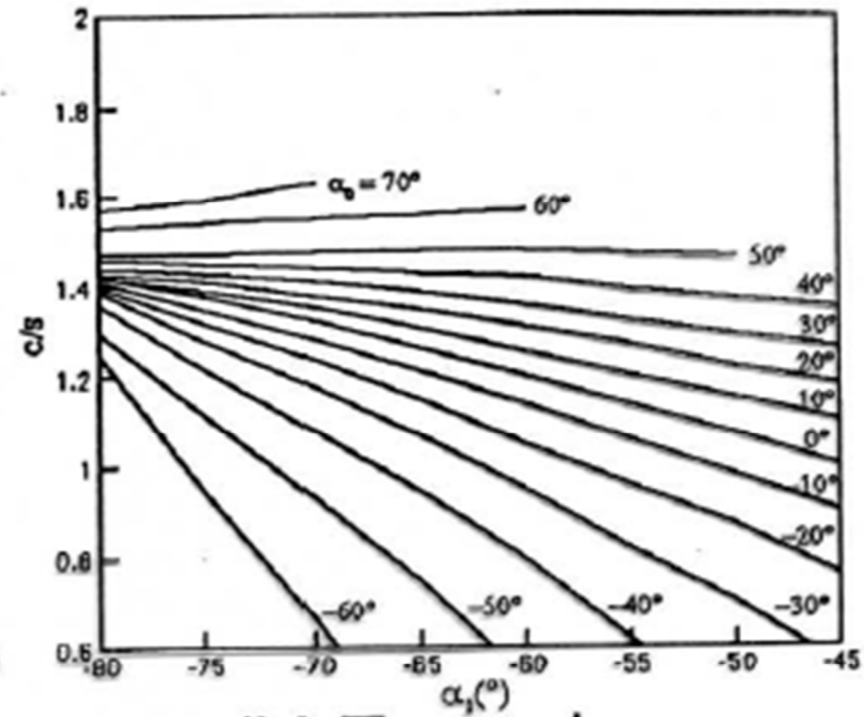


Figura 9.29: Incidenza di stallo e perdite di incidenza per schiere standard ( $s/c = 0.75$ ) (figure a, b) e correzione sull'angolo a valle e sulla incidenza di stallo da utilizzare nei diagrammi a, b quando  $s/c \neq 0.75$  (figure c, d).

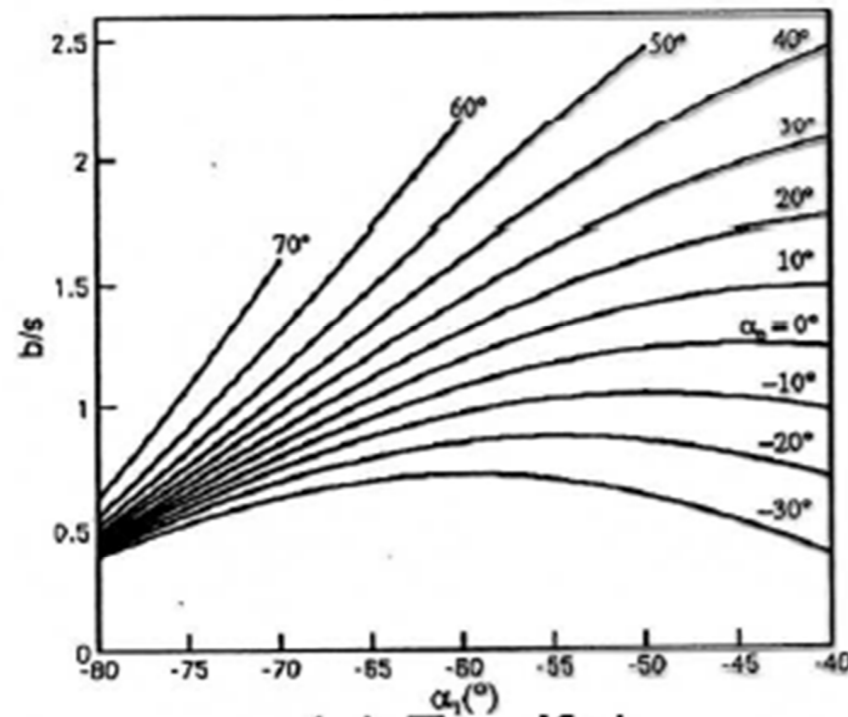
# criteri di carico



(a) Ainley



(b) Traupel



(c) Zweifel

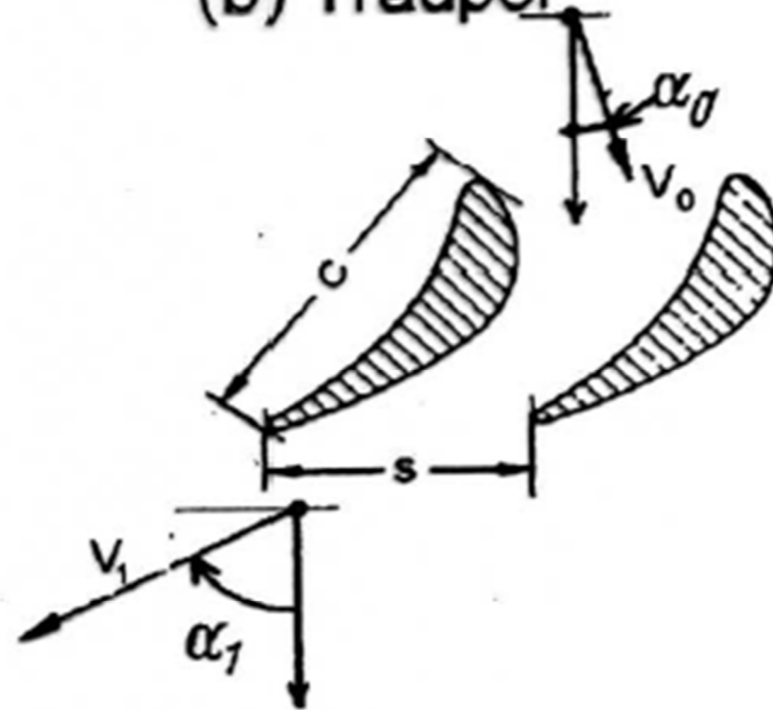


Figura 9.30: Criteri di carico rielaborati da alcuni lavori classici di diversi autori: Ainley e Mathieson (figura a), Traupel (figura b) e Zweifel (figura c).

# criteri di carico

## Criteri di Zweifel

$$\frac{F_t}{F_{t,id}} = \frac{F_t}{\frac{1}{2} \rho b c_1^2} = c_{F_t} = 2 \cos^2 \alpha_1 \left( \frac{c_{m0}}{c_{m1}} \operatorname{tg} \alpha_0 - \operatorname{tg} \alpha_1 \right) \frac{s}{b} = 0,8$$

# criteri di carico

$p_{0_0} = p_{1_0}$  in condizioni ideali

la differenza tra  $p_1$  e  $p_{1_0}$  sarà  $\frac{1}{2}\rho c_1^2$

