

✱ The problem is that we must solve the Prandtl equation
Very difficult task.

$$\begin{cases} \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \\ u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} = -\frac{1}{\rho} \frac{dp}{dx} + \nu \frac{\partial^2 u}{\partial y^2} \\ \frac{\partial p}{\partial y} \approx 0 \end{cases}$$

Solvable only for particular $p(x)$.

One possibility is to integrate about y obtaining the von KARMAN integral equation

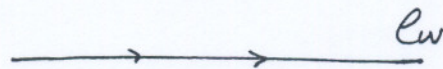
$$U^2 \frac{d\theta}{dx} + (2\theta + \delta^*) U \frac{dU}{dx} = \frac{\tau_0}{\rho}$$

→ $\theta(x)$, $\delta^*(x)$, $\tau_0(x)$

More Simple

FLAT PLATE ANALOGY

car is like a flat plate with ℓ_w



LAMINAR

$$\frac{\partial p}{\partial x} = 0$$

$$\begin{aligned} \delta^* &= 1.72 \sqrt{\frac{\nu x}{U_\infty}} \\ \rightarrow \frac{\delta^*}{x} &= \frac{1.72}{\sqrt{Re_x}} \end{aligned}$$



$$C_f = \frac{\tau}{\frac{1}{2} \rho U_\infty^2} = \frac{0.66}{\sqrt{Re_x}}$$

two sides

$$C_f = \frac{1.32}{\sqrt{Re_x}}$$

TURBULENT

$$\frac{\delta^*}{x} = \frac{0.045}{Re_x^{0.2}}$$

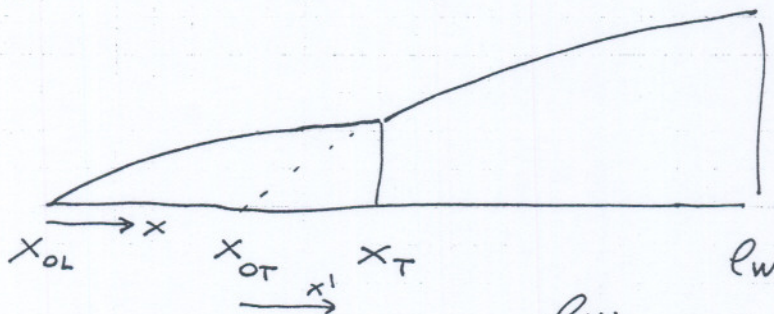
$$C_f = \frac{0.072}{Re_x^{0.2}}$$

much
higher than
the laminar
case

How to estimate d_{friction}

$$d = \int_0^{l_w} \tau_0 dx = \int_0^{l_w} C_f(x) \cdot \frac{1}{2} \rho U_\infty^2 dx$$

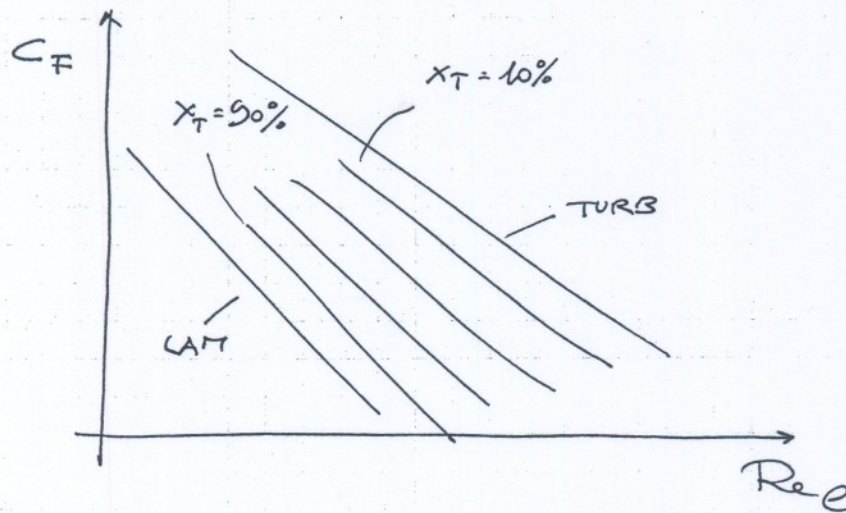
We must have $C_f(x)$
Be careful with transition



$$d = \int_0^{x_T} C_{f, \text{LAM}}(x) \frac{1}{2} \rho U_\infty^2 dx + \int_{x_T}^{l_w} C_{f, \text{TURB}}(x') \frac{1}{2} \rho U_\infty^2 dx$$

This is summarised in a graph

9



where

$$d = C_F \cdot \frac{1}{2} \rho U_\infty^2 l_w (1 + \delta)$$

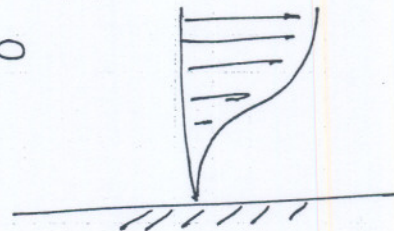
How to control friction drag in 2D

$$C_F \text{ is linked to } \tau = \mu \frac{\partial u}{\partial y}$$

We must reduce $\frac{\partial u}{\partial y}$

goal if we are close to separation !!!

Not nice to have $\frac{\partial p}{\partial x} > 0$

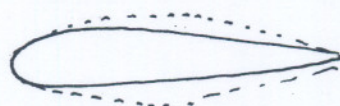


This does not work.

→ it leads to TRANSITION

therefore better to have $\frac{\partial p}{\partial x} < 0$

laminar profiles
useful for
sailboats application



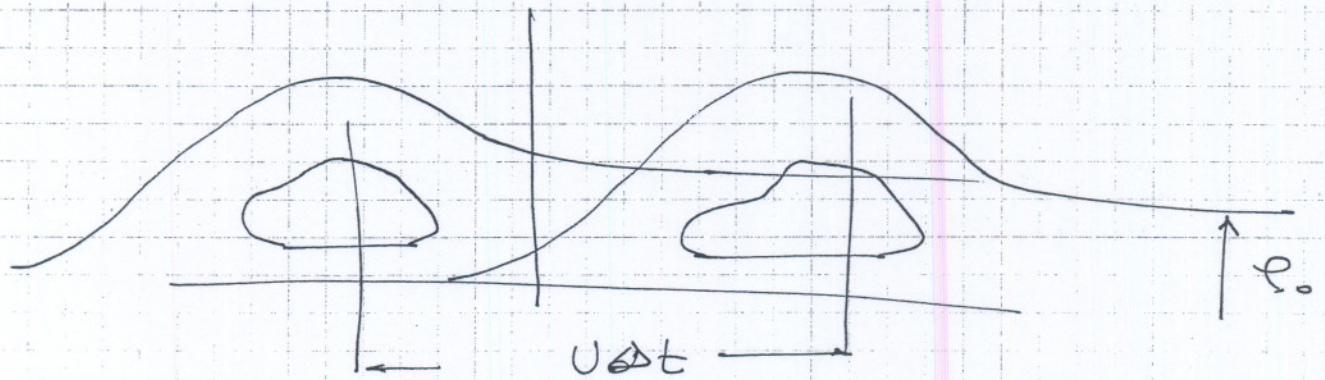
LFC ~~laminar~~ / suction

basically useless for automotive application →

FORM DRAG

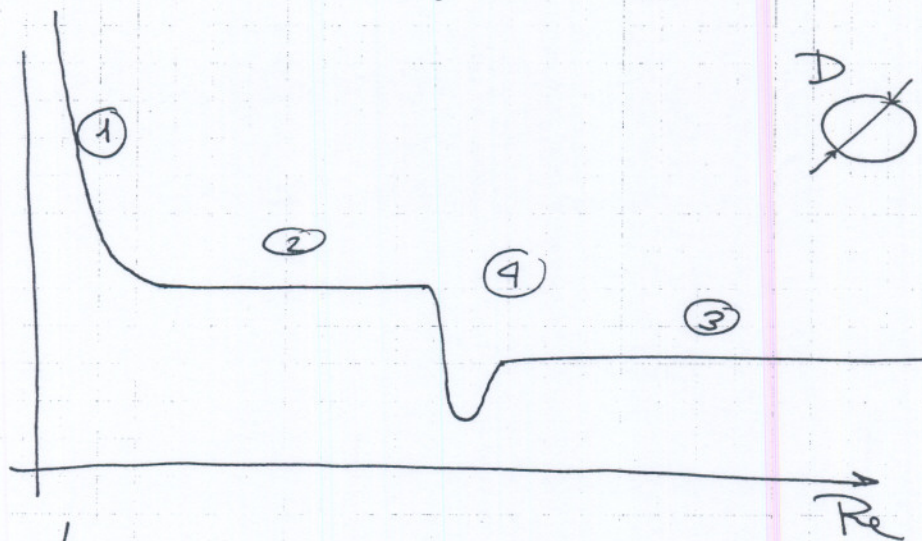
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Due to the presence of the wake



$$\Delta p = p_0$$

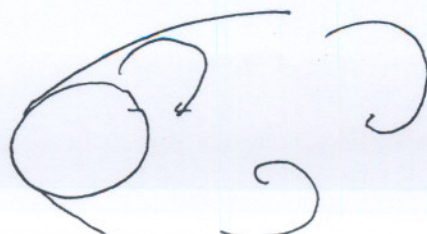
In order to understand how we can decrease it we must refer to shedding from cylinder.



$$C_d = \frac{\Delta p}{\frac{1}{2} \rho U_\infty^2 D}$$

$$\textcircled{1} \quad \Delta p = \frac{\mu U_\infty D}{D} \rightarrow C_H = \frac{\mu U_\infty D}{\frac{1}{2} \rho U_\infty^2 D^2} \approx \frac{1}{Re}$$

② energy in the wake is constant



Separation point is very close to 90°

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V_s is almost $2U_\infty$

$$\omega = \int_0^\delta \frac{\partial u}{\partial y} dy \approx \int_0^\delta \partial u \approx V_s$$

The amount of vorticity shed in the wake is quite big.

③ Supercritical region

Separation is at about 120°

V_s is smaller



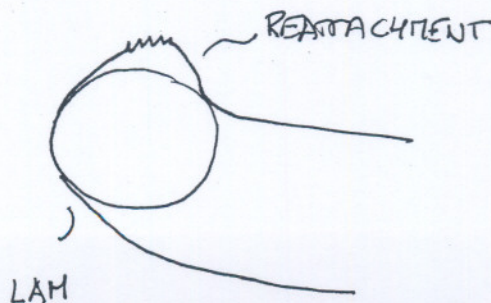
How it is possible to decrease C_D ?

~~INSERT~~

1) ~~That produce less or reduce the intensity of the vorticity that you shed in the wake~~

~~$\parallel U_\infty \parallel \sim V_s$~~

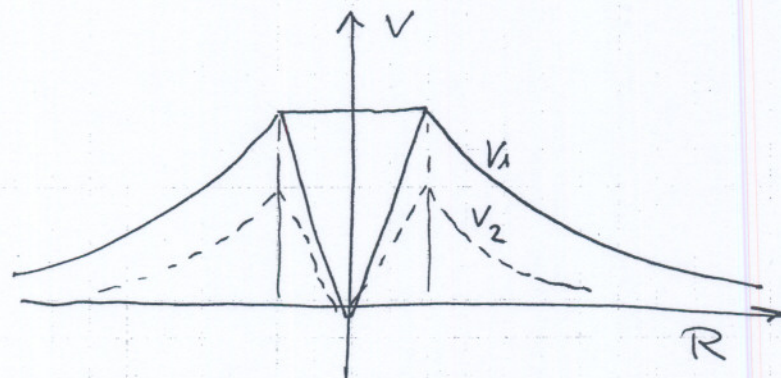
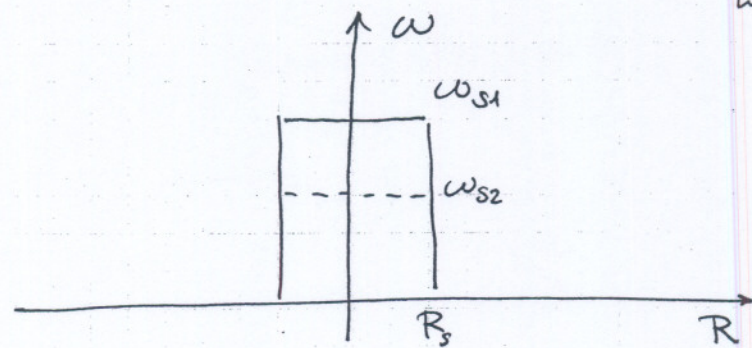
④ Critical region - Separation line is not a line $\rightarrow$ no shedding of vortices



WAKE MODEL

12a

Train of RANKINE VORTICES - Effects of intensity.

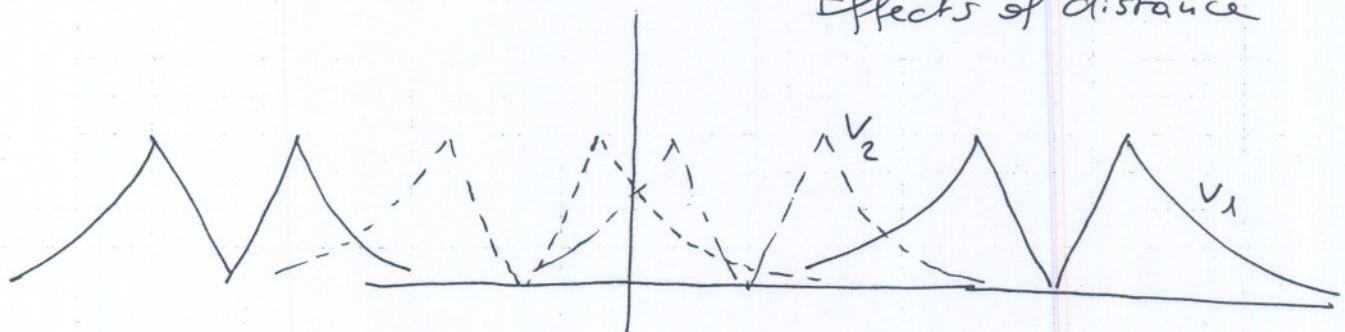


So first of all reduce ω_s

$$|V_1| > |V_2|$$

$$e_{o1} > e_{o2}$$

Effects of distance



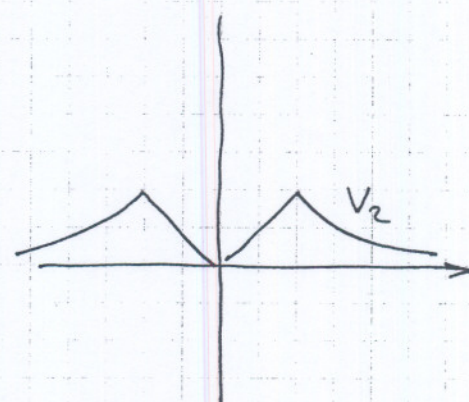
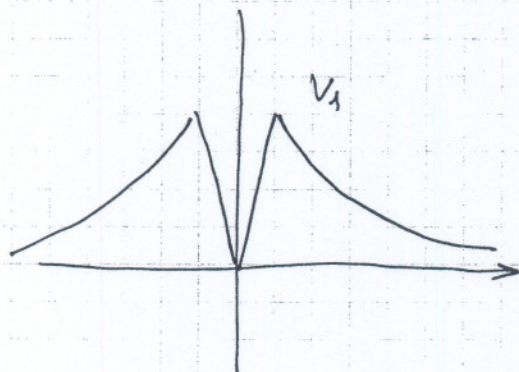
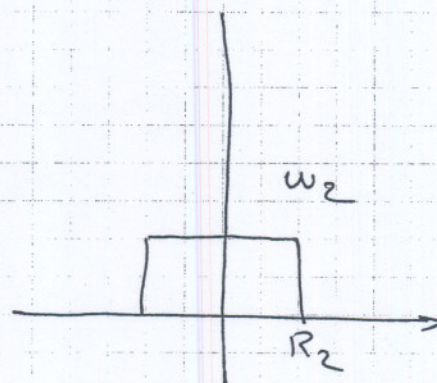
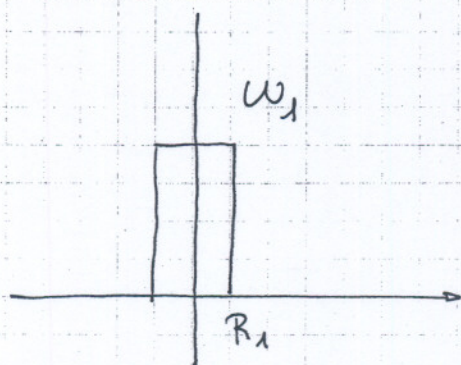
In the centre of the wake energy increase when we put them close. Outside it decreases.

Totally $e_{o1} > e_{o2}$

On the limit of $\delta_{wake} \rightarrow 0$ $e_o \rightarrow \emptyset$

VERY IMPORTANT!

Effect of concentration



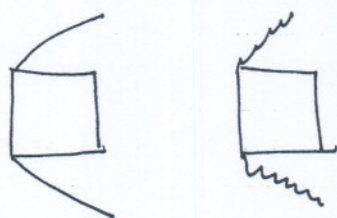
$$c_{o1} > c_{o2}$$



- 1) INTENSITY
- 2) DISTANCE
- 3) CONCENTRATION

Now if instead of a cylinder we have different geometries : see Fig 8 Buresti:

- a) Squared corners → Fixed separation (case 1)
→ avoid reattachment



(case 2) A small curvature allows a reattachment



(Case 3) reduce the dimension of the wake



Case 4-7 Effect of orientation



Case 6 → Basically it is an aerodynamic body.



Mechanism to reduce form drag.

a) - Delay separation

by means of:

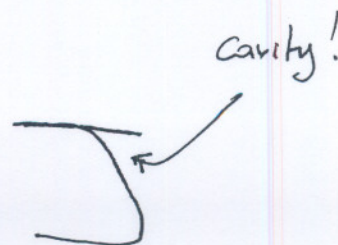
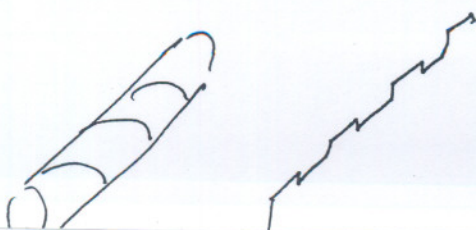
- shaping.
- transition (roughness)
- suction
- blowing.

effects.

- p increases
- w decreases
- distance between vortices decreases

→ BE CAREFUL TO NOT INTRODUCE ENERGY !!!

b) Destroy regularity



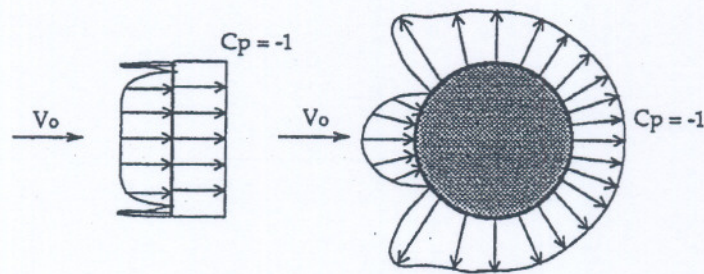


Fig. 7 – Comparison between the pressure distributions of a flat plate ($C_D = 2$) and of a circular cylinder for $Re < 10^5$ ($C_D = 1.2$)

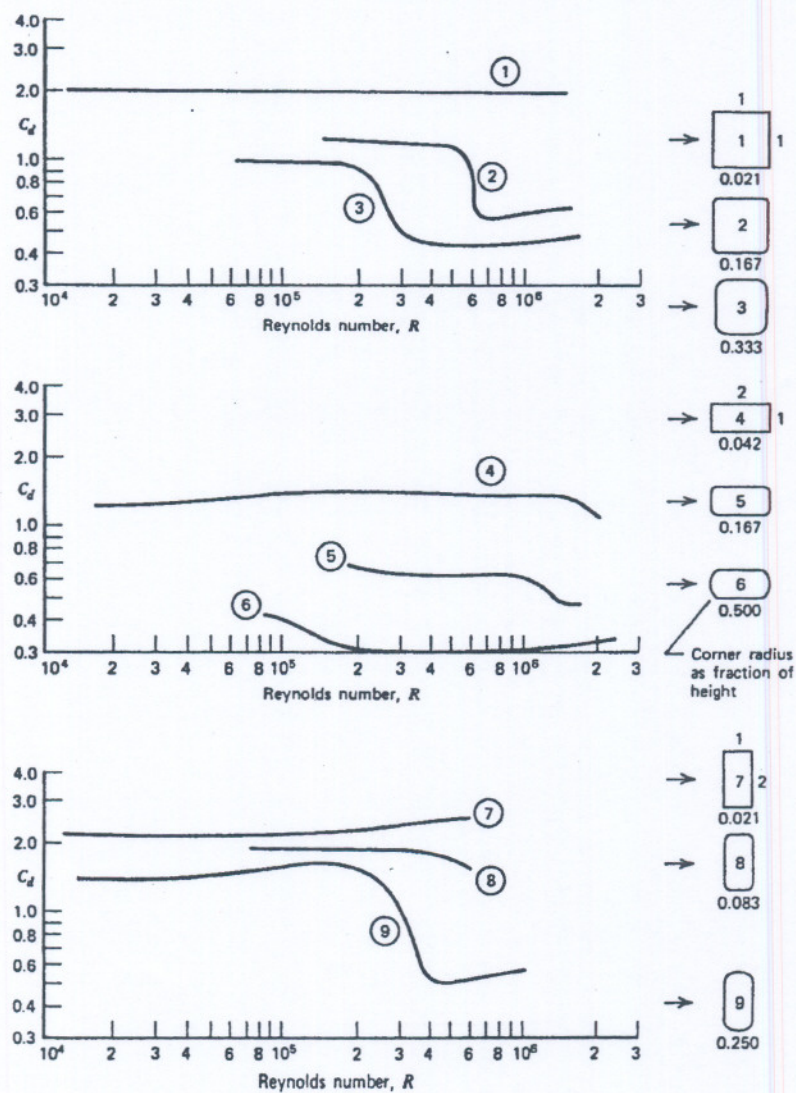


Fig. 8 – Drag coefficients of various cylindrical shapes as a function of Re .

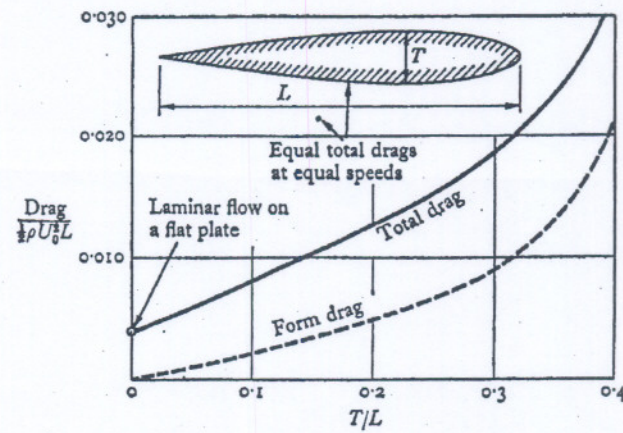
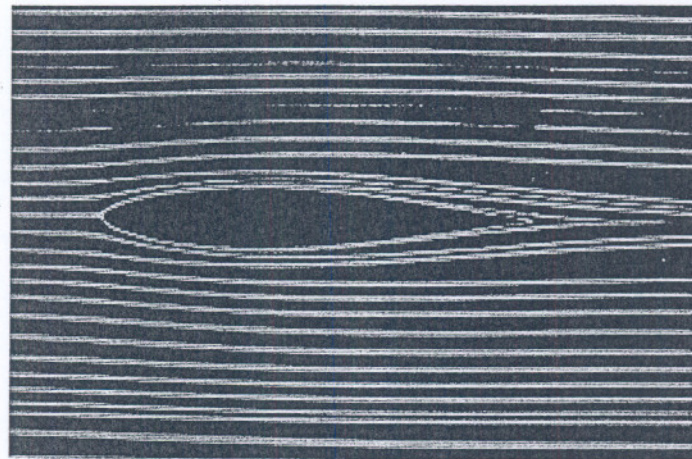
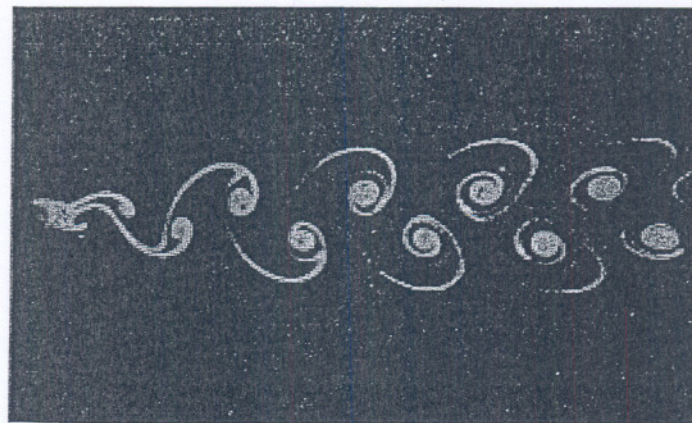


Fig. 9 – Comparison between an airfoil and a circular cylinder having the same total drag (from Batchelor 1967).



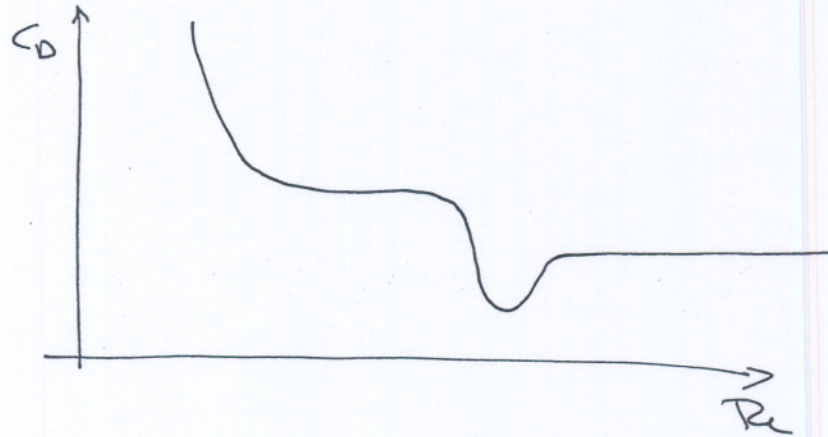
a)



b)

Fig 10 – Flow fields around an airfoil and a circular cylinder (from Van Dyke 1982).

Drag from circular cylinder and spheres



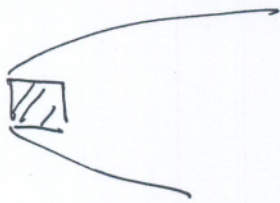
Drop in C_D between 10^5 and 10^6

- Amount of vorticity
- Distribution
- Concentration

—

- Effect of roughness $\rightarrow$ anticipation of transition. Effective only in a certain range of Reynolds numbers.
- Effect of rounded corners
Of course it depends on the Reynolds number.
(SLIDE 22) - FIRST Observe the presence of the 'critical region'
The decrease is due to the decrease of separation bubbles.
- Effects of length and shape

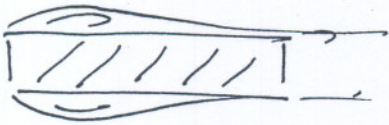
②



$$C_D = 2.2$$



$$C_D = 1.6 \quad (\text{shall reattachment})$$



$$C_D = 1.0 \quad (\text{strong reattachment})$$

Cornered
in front



$$C_D = 0.6$$

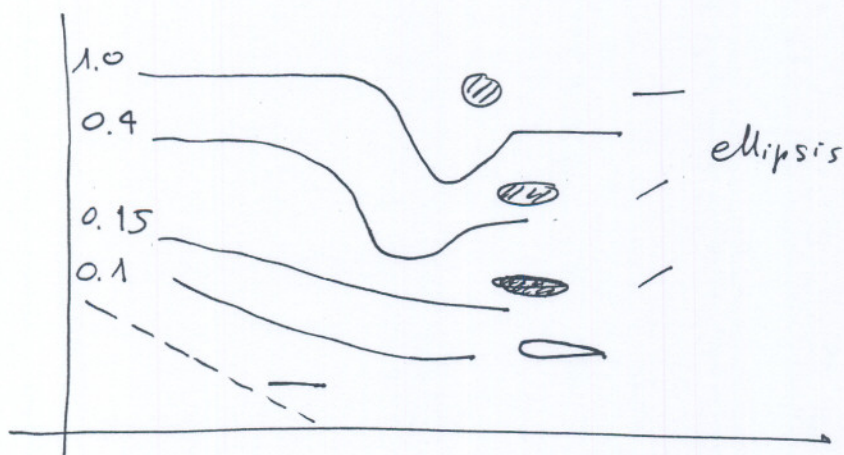


$$C_D = 0.4$$

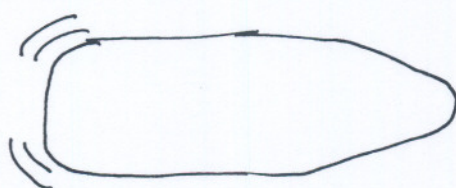
Mechanism to reduce drag (form drag)

a) Delay separation

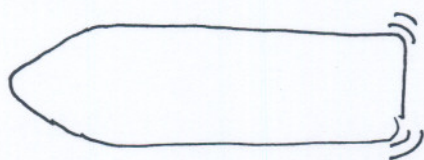
- shaping.



- transition (roughness)
- suction
- blowing.
- guide fins

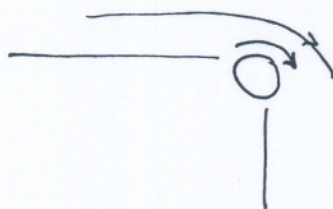


from 0.71 $\rightarrow$ 0.27



0.58 $\rightarrow$ 0.26

- other devices

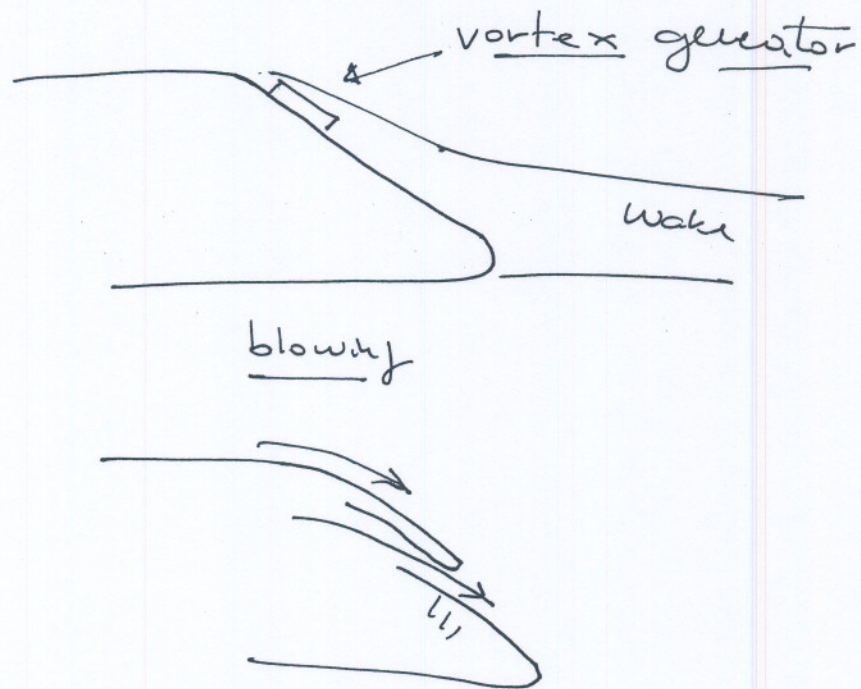


effects

- ϕ increases
- w decreases
- distance between vortices decreases

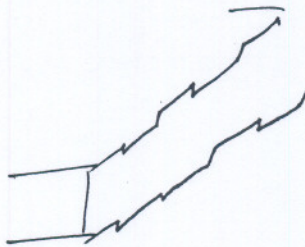
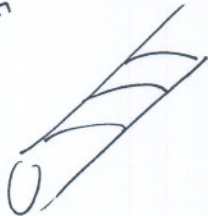
Be careful - Don't introduce energy!

④



Destroy regularity

Separation



Splitter plates



Cavities



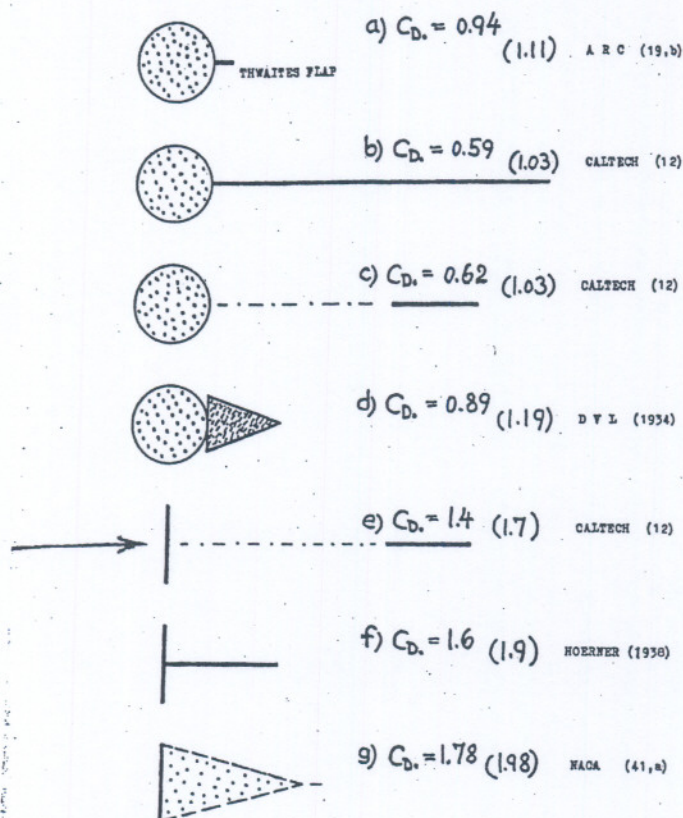


Figure 8. Influence of "splitter" plates (and similar devices) on the drag coefficient of vortex-street-producing shapes (tested between walls). The values in brackets are the drag coefficients without wake interference. The Reynolds numbers (on d or h) are between 10^4 and 10^5 .

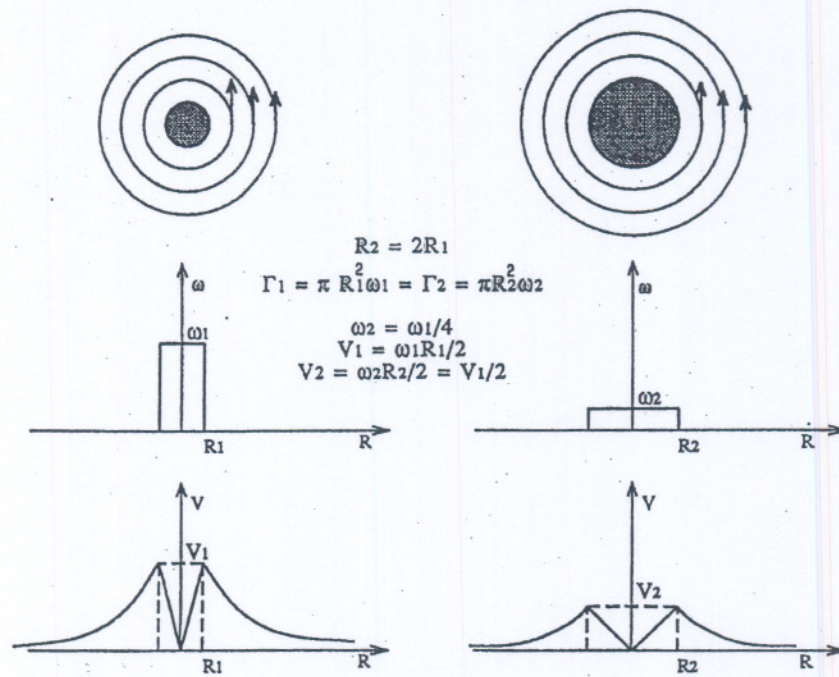


Fig. 11 – Velocity and vorticity fields of two ideal vortices having the same global vorticity but different radius.

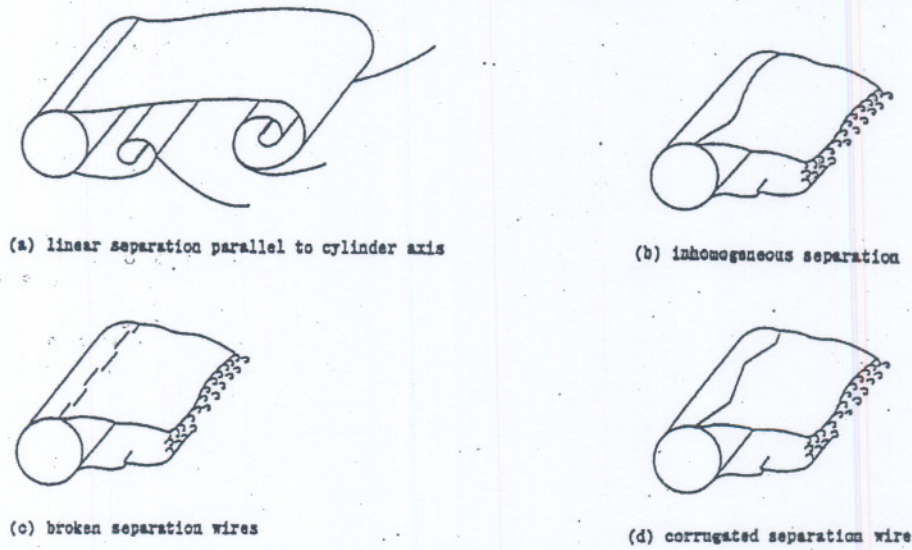
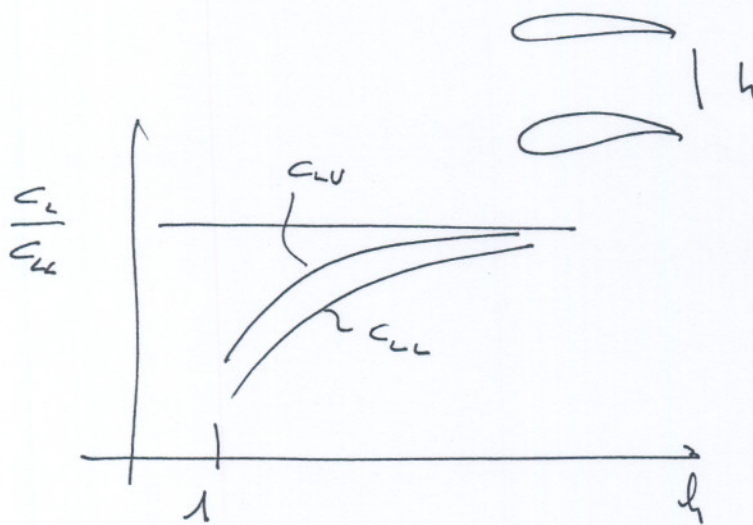
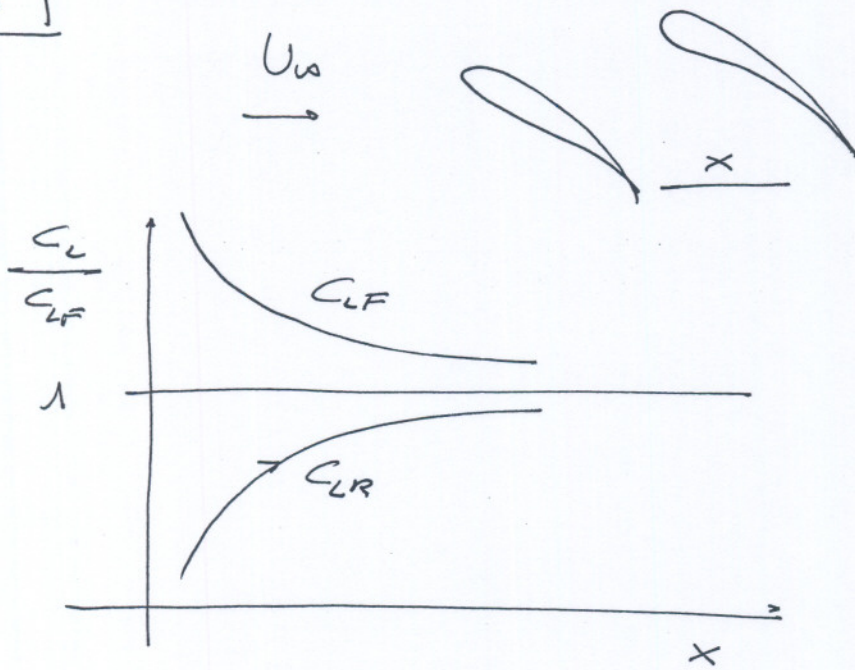


Fig. 12 – Influence of separation line on wake structure for a circular cylinder

Interference effects

5

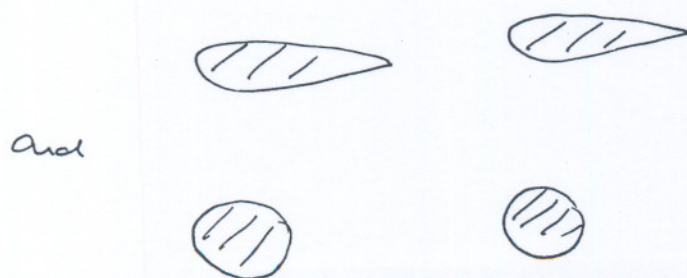
LIFT



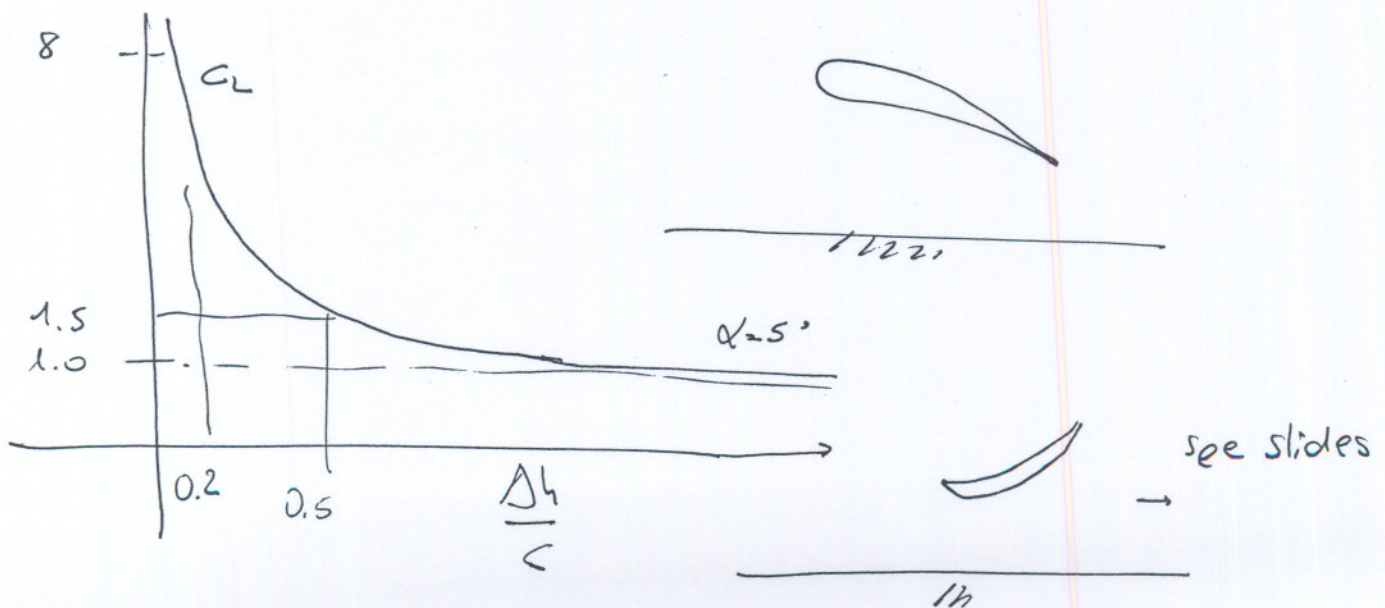
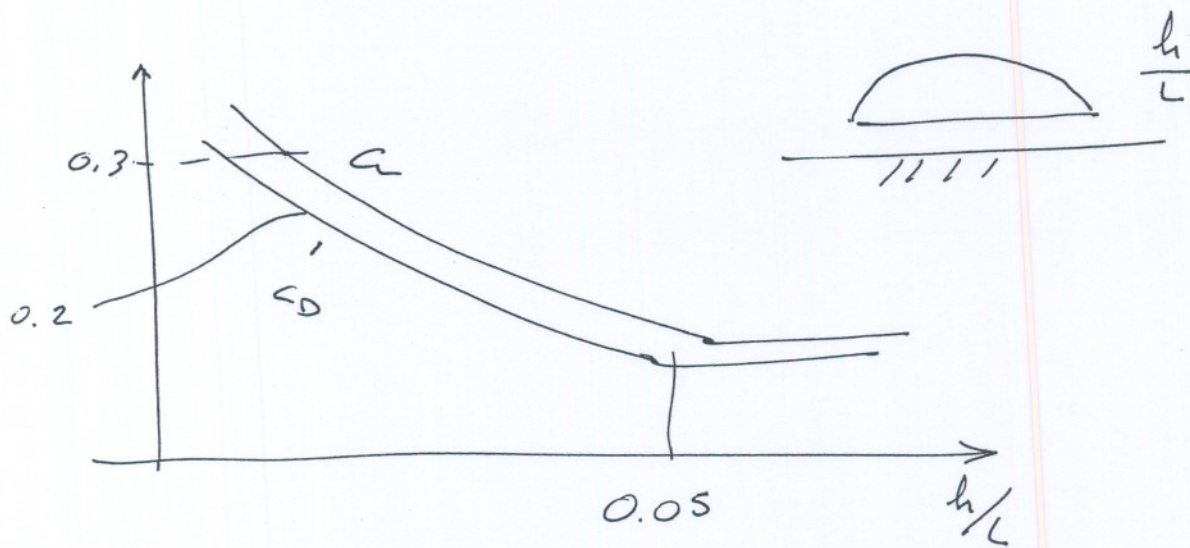
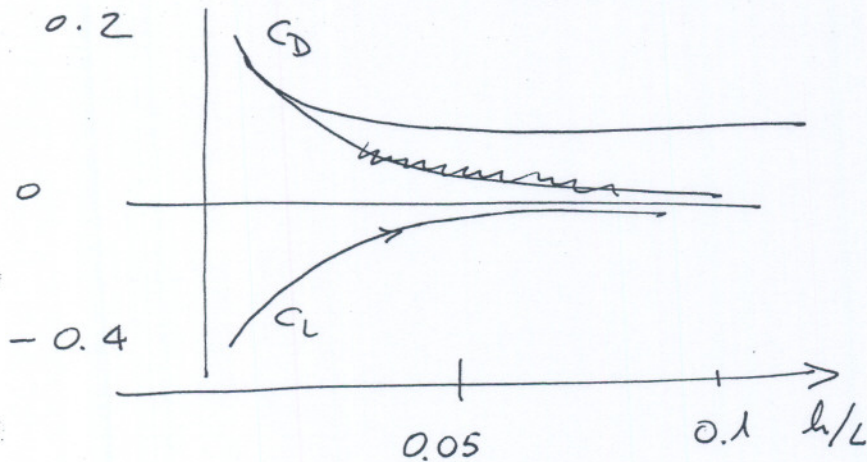
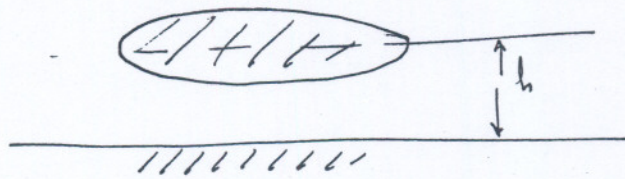
DRAG

See SLIDE from HOERNER

Fig 2 and 3.



Ground effects elliptic bodies





Es. A: 7 - MODIFICHE ALLA GEOMETRIA

DIPARTIMENTO
DI INGEGNERIA
AEROSPAZIALE

In base alle analisi precedenti si può modificare la geometria

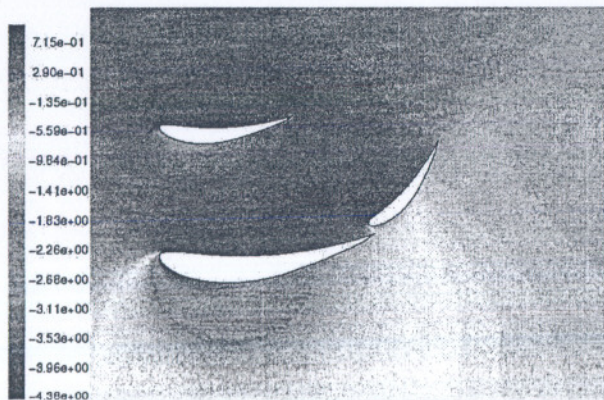
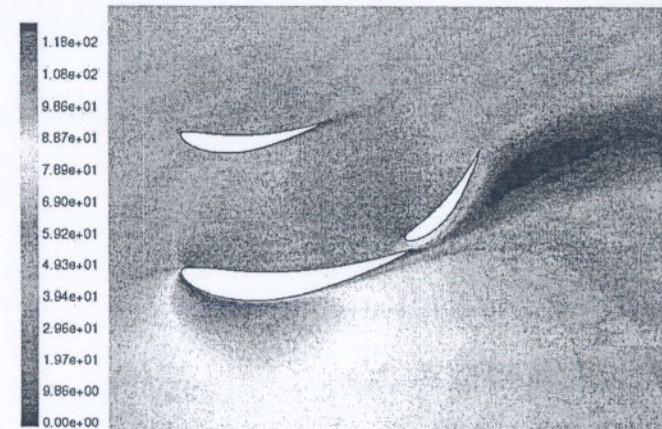


RIPETIZIONE DELL'ANALISI

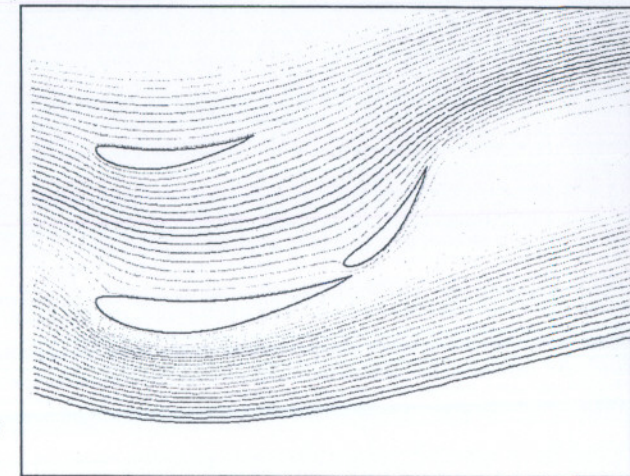
Es: Wing 5 MFU – AOA -2°

Wing	Type	AOA (°)	V (m/s)	Cx	Cz	Cd	Cl	Fx/q	Fz/q
5	MFU	-2	56,5	0,307	-3,085	0,199	-3,094	0,107	-1,080
5	MFU Small	-2	56,5	0,296	-3,343	0,179	-3,351	0,104	-1,170
5	MFU Aft	-2	56,5	0,313	-3,394	0,194	-3,403	0,110	-1,188
5	MFU Last	-2	56,5	0,314	-3,316	0,198	-3,325	0,110	-1,161

Wing	Type	AOA (°)	V (m/s)	Contribution to vertical load			Efficiency	
				Main	Flap	Upper	Cz/Cx	Cl/Cd
5	MFU	-2	56,5	80,2%	13,1%	6,8%	10,05	15,54
5	MFU Small	-2	56,5	83,7%	13,2%	3,1%	11,29	18,71
5	MFU Aft	-2	56,5	81,5%	12,7%	5,7%	10,84	17,51
5	MFU Last	-2	56,5	79,7%	11,9%	8,5%	10,56	16,79



Pressure Coefficient Velocity

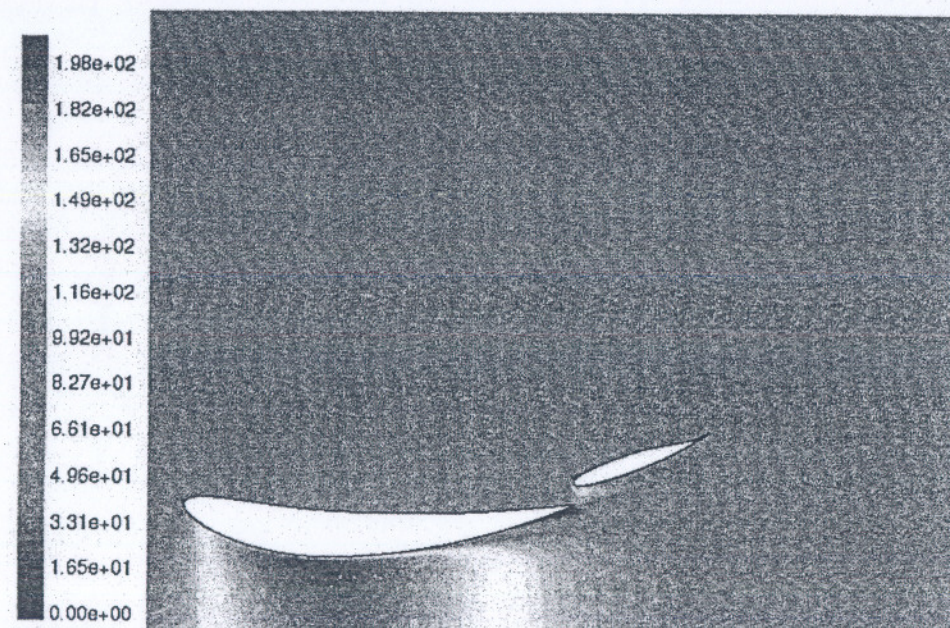




CODICI RANS - esempio effetto suolo

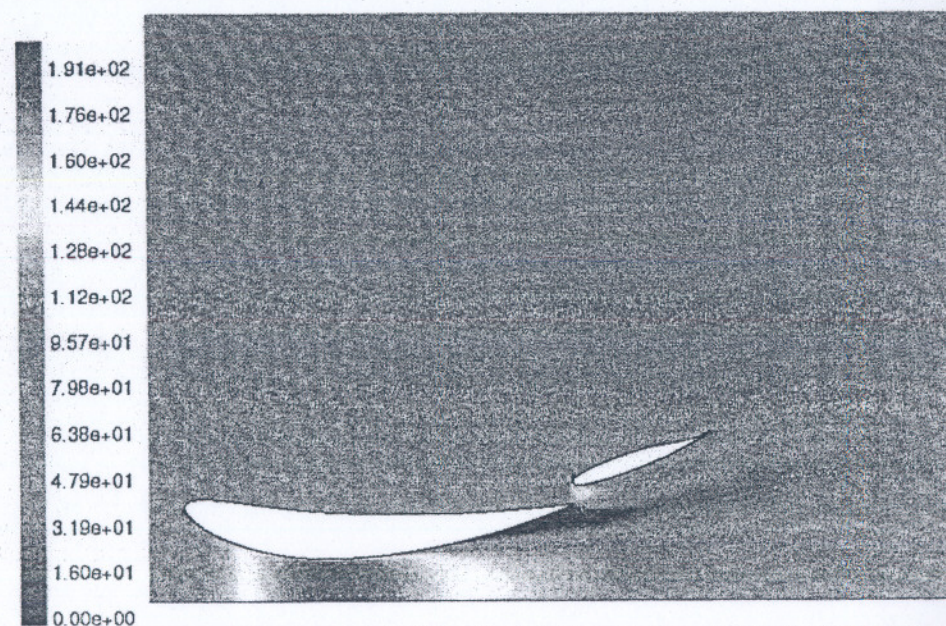
DIPARTIMENTO
DI INGEGNERIA
AEROSPAZIALE

$h = 7 \text{ cm}$ $\longrightarrow$ $h = 3 \text{ cm}$



Contours of Velocity Magnitude (m/s)

Aug 03, 1999
FLUENT 5.0 (2d, coupled exp, ke)

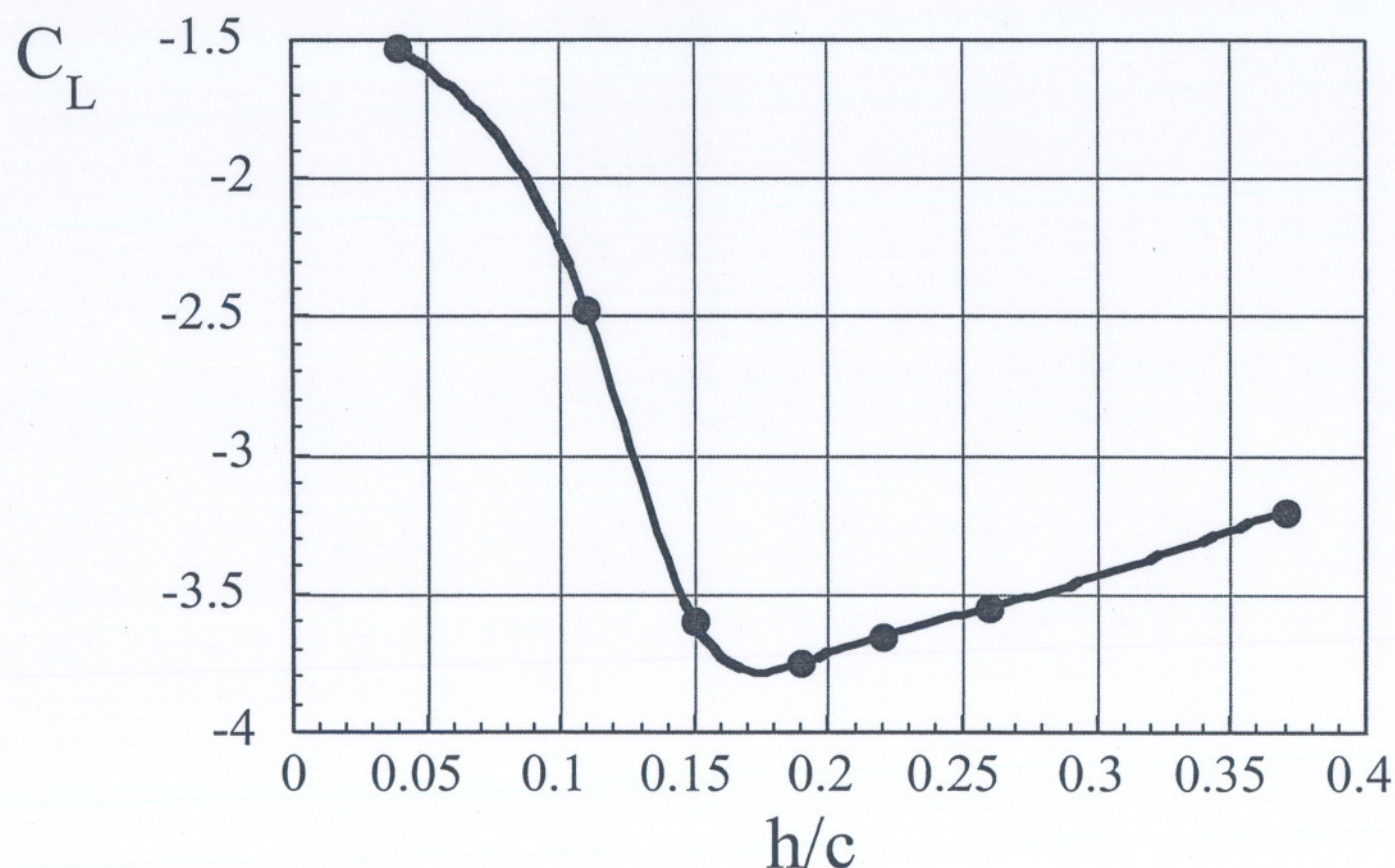


Contours of Velocity Magnitude (m/s)

Aug 03, 1999
FLUENT 5.0 (2d, coupled exp, ke)



Analisi della portanza dell'alettone anteriore al variare della distanza dal suolo



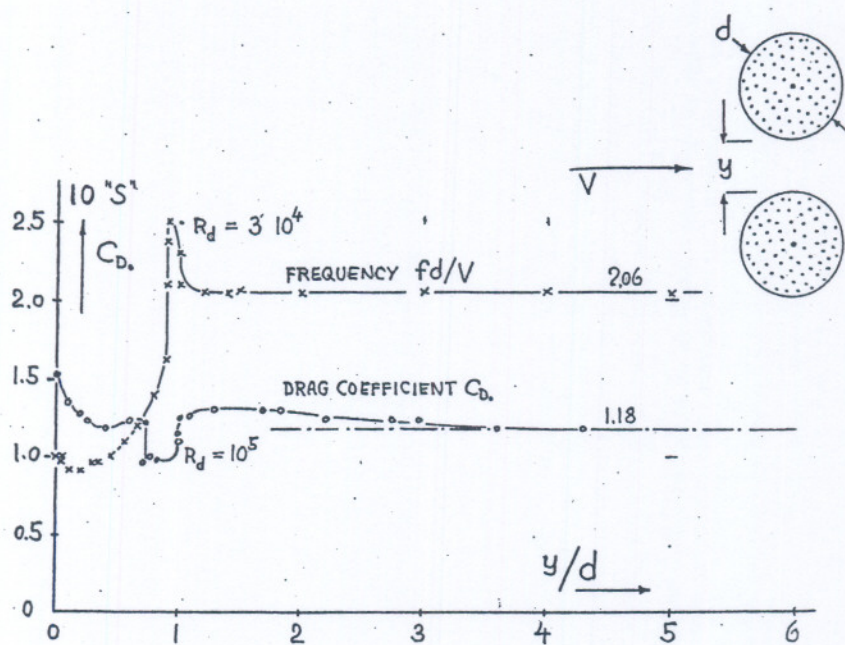


Figure 5. Drag (2,a) (and vortex-street frequency, reference 2,b) of a pair of circular cylinders placed side by side.

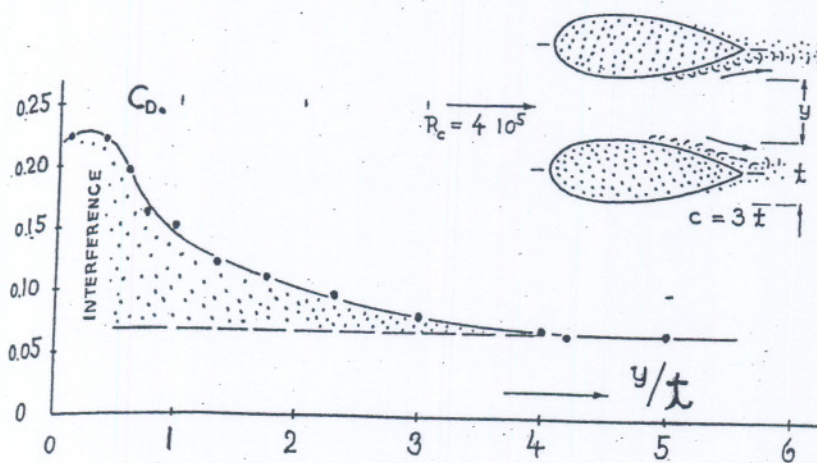


Figure 6. Drag of a pair of struts, one beside the other (2,a).

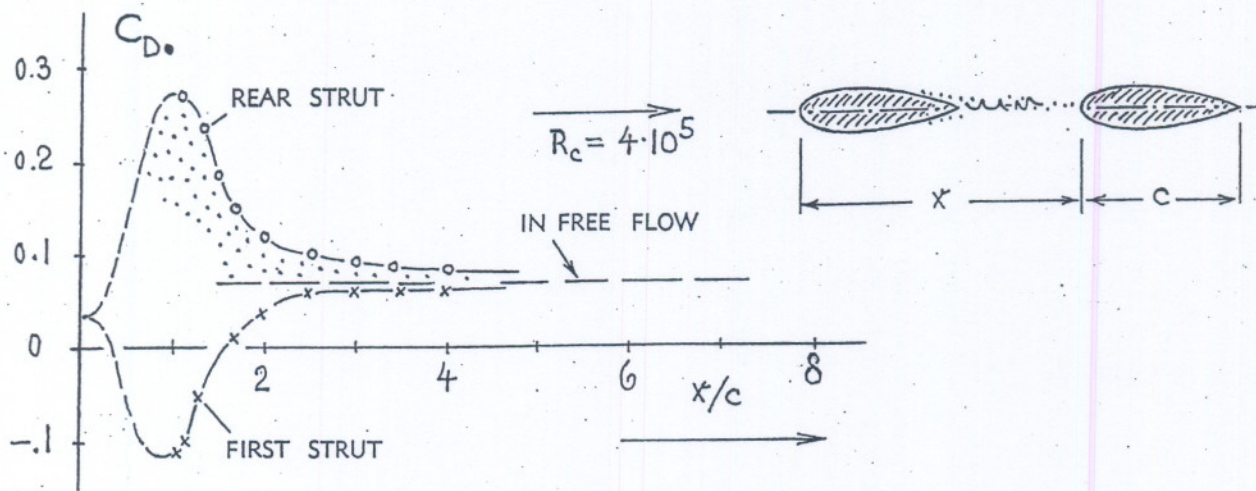


Figure 3. Drag of a pair of strut sections, one behind the other, in tandem (2,a).

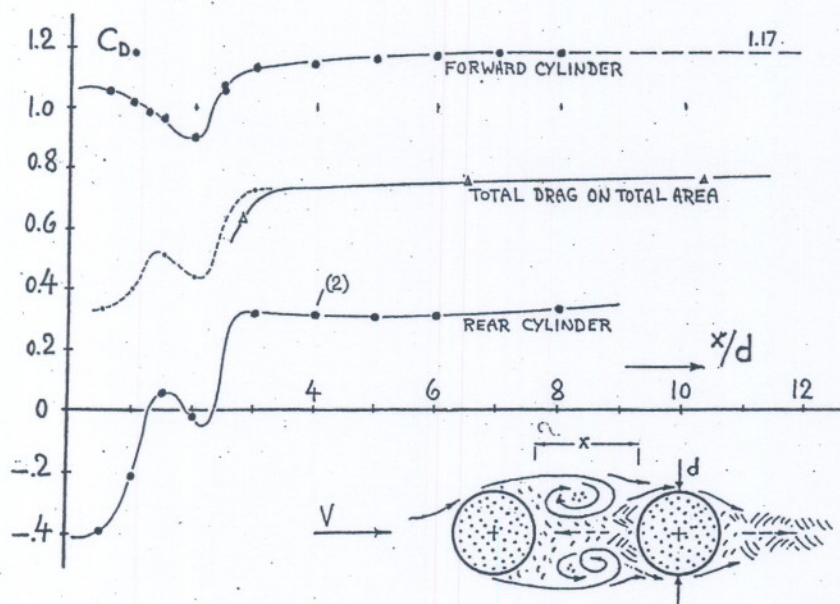


Figure 2. Drag coefficients of two circular cylinders, one placed behind the other.

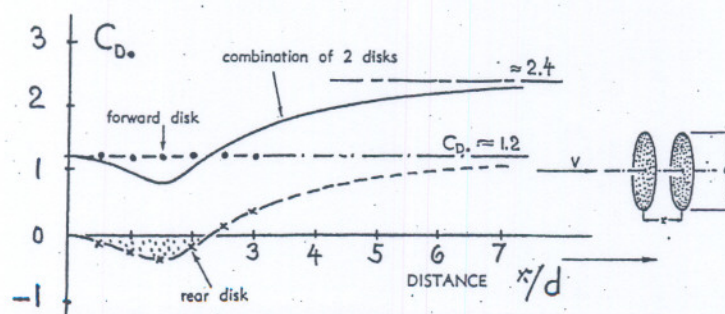


Figure 1. Interaction between two disks placed one behind the other; (reference 1,a).