

FORCES ON BODIES

Aerodynamic force $\begin{cases} \text{pressures} \\ \text{shear stresses} \end{cases}$

→ LIFT Component perpendicular to $\vec{U}_\infty$

$$L = \frac{1}{2} \rho U_\infty^2 S C_L$$

→ DRAG Component parallel to $\vec{U}_\infty$

$$D = \frac{1}{2} \rho U_\infty^2 S C_D$$

→ MOMENT (PITCH)

$$M = \frac{1}{2} \rho U_\infty^2 S L C_m$$

→ Brute force $\begin{cases} \text{distribution of pressure} \\ \text{distribution of shear stress} \end{cases}$



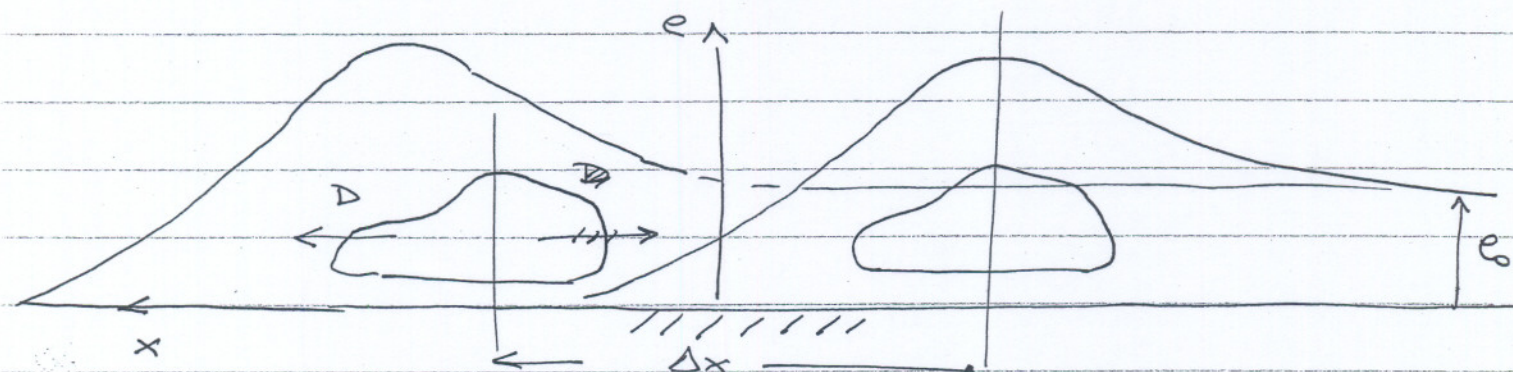
NEED FOR SIMPLIFIED SCHEMES

L → due to pressure distribution (1)

D $\begin{cases} \text{pressure} \begin{cases} \rightarrow \text{INDUCED DRAG} \\ \rightarrow \text{FORM DRAG} \end{cases} \\ \text{shear stress} \rightarrow \text{FRICTION DRAG} \end{cases} \left. \vphantom{\begin{matrix} \text{pressure} \\ \text{shear stress} \end{matrix}} \right\} \begin{matrix} \text{PROFILE DRAG} \\ \text{2D} \end{matrix}$

(1) viscous stresses may contribute with 1%-2% ~~stresses~~

Energy interpretation of drag.



$e(x)$ — energy contained in a plane of fluid [Joule/m]

$$\int_{-\infty}^{+\infty} e(x) = E \quad \text{Total energy of the fluid}$$

$$\mathcal{L} = \Delta E$$

$$\text{but } \mathcal{L} = -D \cdot \Delta x = -D U \Delta t$$

$$\Delta E = e_0 \Delta x = e_0 U \Delta t$$

$$\text{then } -D = e_0 \Rightarrow D = -e_0 \quad \text{NEGATIVE!!!}$$

directed against the motion ↙

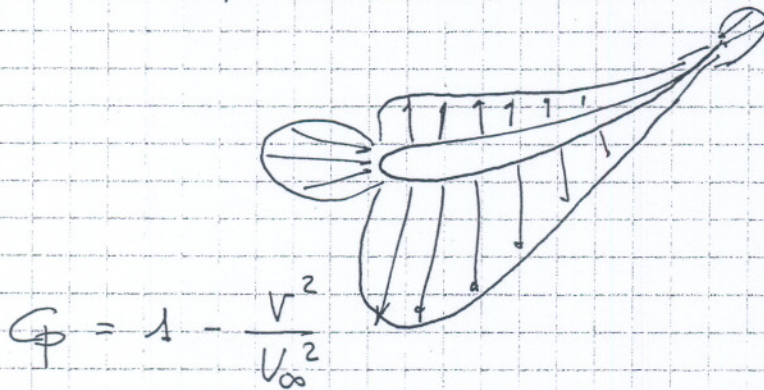
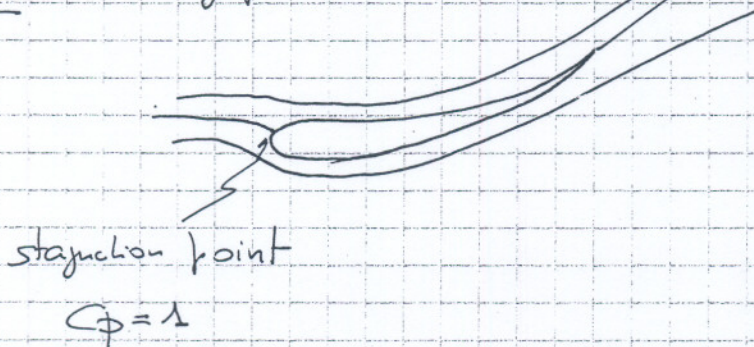
One strategy to evaluate ~~pressures~~ ^{forces} acting on bodies

VERY GOOD FOR AERODYNAMIC
? FOR BLUFF.

ITERATIVE PROCEDURE.

- 1) $\nabla \cdot \mathbf{v} = 0$ every where on the body's surface
Solve the flow with the potential equation ①

AERO (Wing profile at low angle of attack)



acceleration $\rightarrow$ curvature
velocity $\rightarrow$ thickness

Integrating the pressure distribution

$$D = 0$$

$$L \neq 0$$

e.g. with some hypotheses $\rightarrow C_L \approx 2\pi(\alpha - \alpha_0)$

①

$$\begin{cases} \nabla^2 \phi = 0 \\ \frac{\partial \phi}{\partial n} = 0 \text{ (surface)} \\ \text{grad } \phi|_{\infty} = \vec{U}_{\infty} \end{cases}$$

→ Conformal mapping

→ Thin airfoil theory

→ Numerical schemes

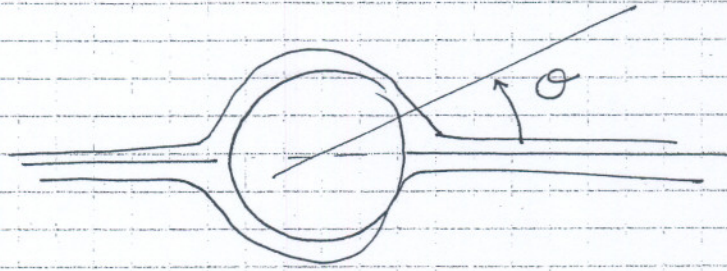


Results

Problems → KUTTA CONDITION

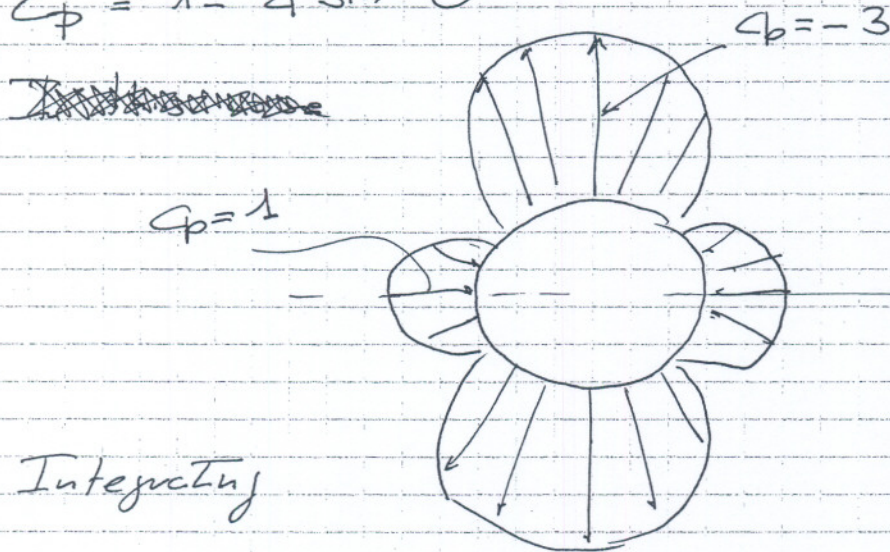
We must provide the points of separation

Flow around a cylinder.



$$V^2 = 4U_\infty^2 \sin^2 \theta$$

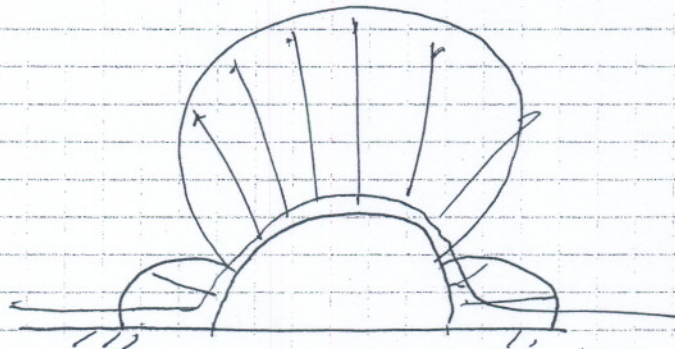
$$C_p = 1 - 4 \sin^2 \theta$$



Integrating

$$L = 0$$

$$D = 0$$



The effect of the ground.

$$D = 0$$

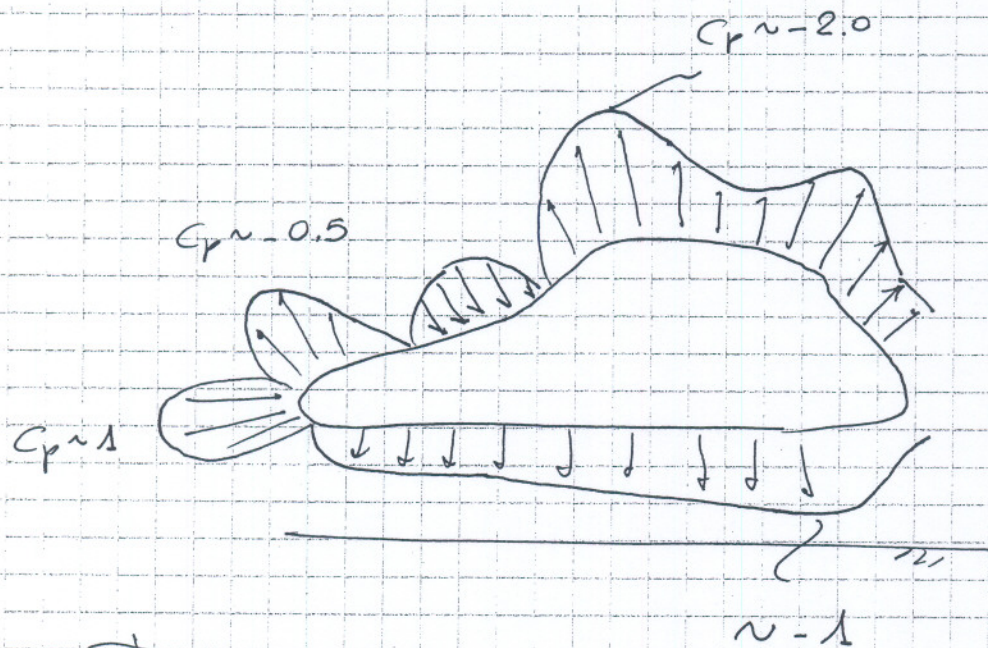
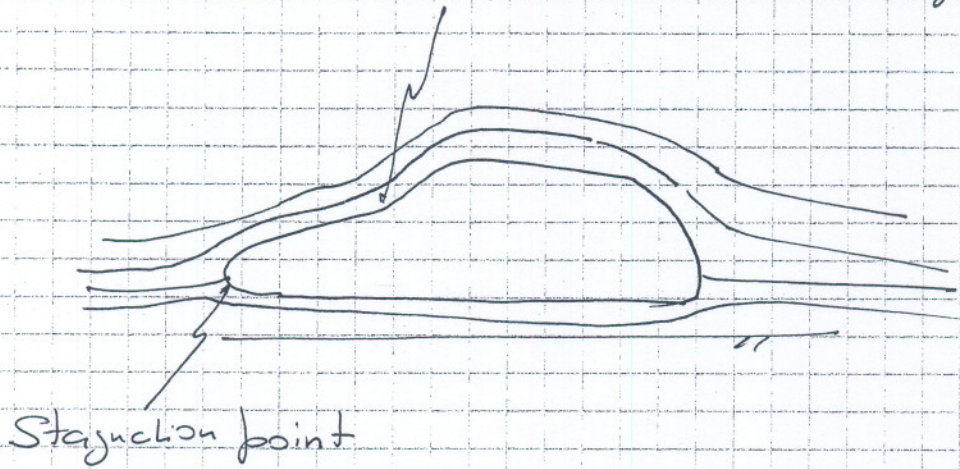
$$L \neq 0$$

$$C_L = -\frac{5}{3}$$

like a FORMULA INDY CAR !!!

car

if cornered we have stagnation point



$$\nabla \cdot \mathbf{V} = 0$$

$$L \neq 0$$

ITERATIVE PROCEDURE

STEP 2

Ex. Steady Flow $\frac{\partial}{\partial t} = 0$

Once you have ϕ and $\vec{V}$ around the body you can enter the Prandtl model

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

$V_e \frac{\partial V_e}{\partial x}$ INPUT!!

Boundary conditions

$$u(x, 0) = v(x, 0) = 0$$

$$\left. \frac{\partial u}{\partial y} \right|_0 = \left. \frac{\partial^2 u}{\partial y^2} \right|_0 = 0$$

$$u(x, y) \quad v(x, y) \quad \begin{matrix} \searrow \delta \\ \searrow \tau(x) \end{matrix}$$

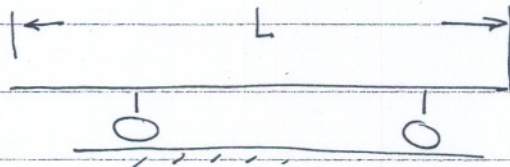
This is a quite complex calculation for general bodies - The calculation of τ is STILL a Problem.

⇒ You need to resolve very close to the wall
Also CFD has a lot of problems.

A first estimation of skin friction can be done by means of FLAT PLATE Results.

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

$$U_e = U_\infty$$



The system can be solved

$$C_D = \frac{2.656}{\sqrt{Re_L}}$$

Flat plate solution - BLASIUS

$$C_f = \frac{\tau}{\frac{1}{2} \rho U_\infty^2} = \frac{0.664}{\sqrt{Re_x}}$$

$$C_f = \frac{1}{L} \int_0^L C_f(x) dx = \frac{1.328}{\sqrt{Re_L}}$$

For turbulent boundary layer

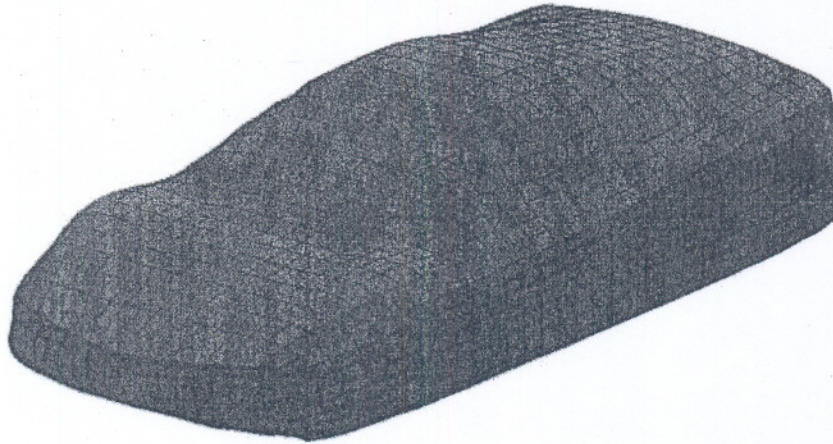
$$C_f = \frac{0.0592}{Re_x^{0.2}}$$

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

On a general body we have the effects of $\frac{\partial P}{\partial x}$

Another output from the boundary layer method is the b.l. thickness distribution

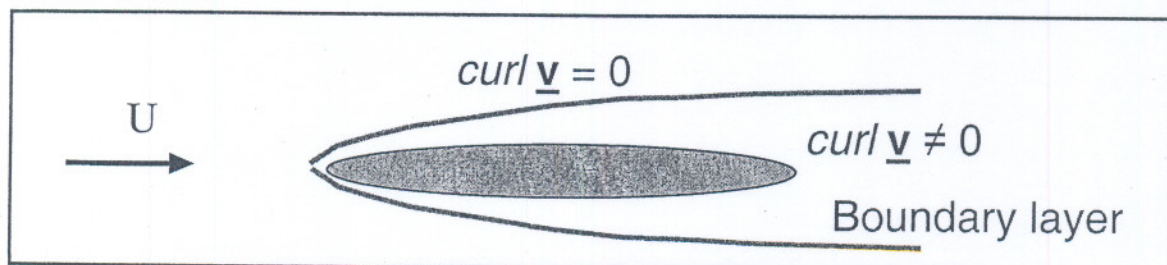
THE USE OF POTENTIAL FLOW IN CAR AERODYNAMICS



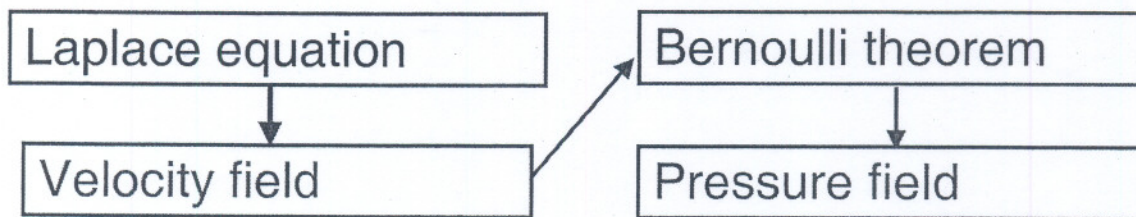
Classic aeronautical approach

The flow field is analysed in term of vorticity
ORIGIN and DYNAMICS

The flow field can be divided in two regions:

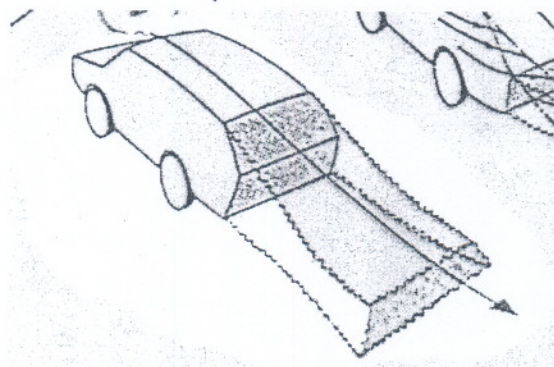


- If the boundary layer remains thin then the pressures are the same as the ones acting on the border of the b.l.
- Where $\text{curl } \mathbf{v} = 0$, if the flow is incompressible ($M < 0.3$), then



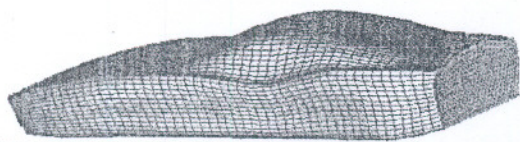
High performance cars may be considered slender bluff bodies where separation of the b.l. is limited to the very end of the body

THE EFFECT OF THE WAKE ON THE FLOW FIELD UPSTREAM OF THE SEPARATION POINT MUST BE TAKEN INTO ACCOUNT

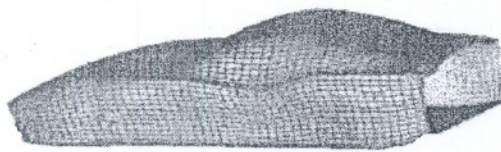


the potential flow solver can be correctly applied if:

- The separation line is at the very end of the body
- ➔ • It is uniquely determined by the car geometry
- The wake is modelled like a natural continuation of the body and is treated like a solid surface



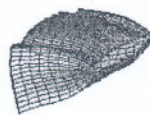
The car surface is divided
in two parts



forebody



base



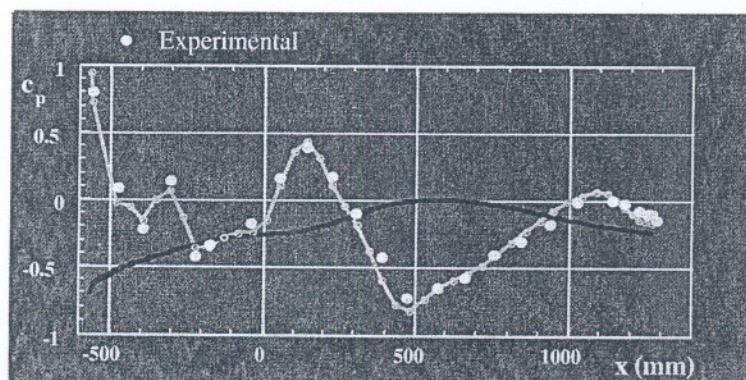
The virtual body that represents
the near wake is modelled

Computational body



The final computational body is
forebody + "virtual"

An experimental analysis has been carried out at the
FERRARI wind tunnel to validate the procedure
The shape and dimensions of the car are similar to a
normal production car scale 1:2.5

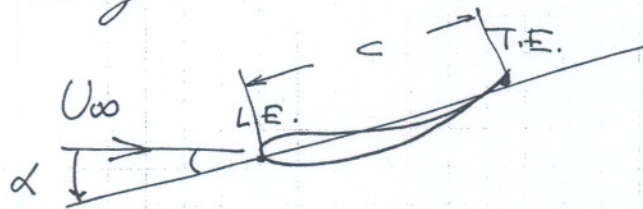


Forces on Aerodynamic bodies.

2D

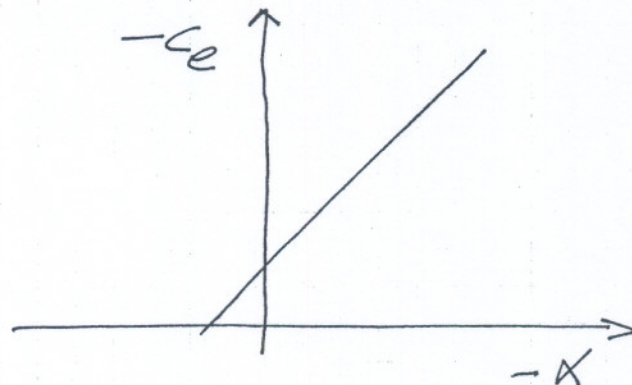
- Boundary layer attached
- We can use potential flow results

e.g. wing



We have the chord
the angle of attack.

$$-C_e = \frac{e}{\frac{1}{2} \rho V_{\infty}^2 c}$$

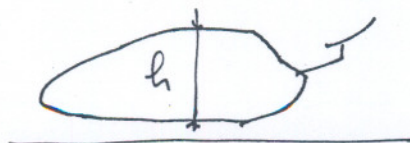


$$C_e = 2\pi(\alpha - \alpha_0)$$

SLOPE IS 2π

Be careful!

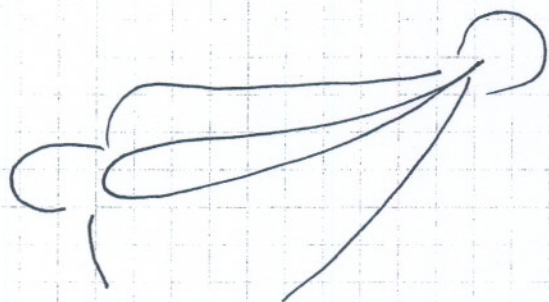
- Contribution to $C_{e,car}$



$$\Delta C_{e,car} = \frac{C_e \cdot c}{h}$$

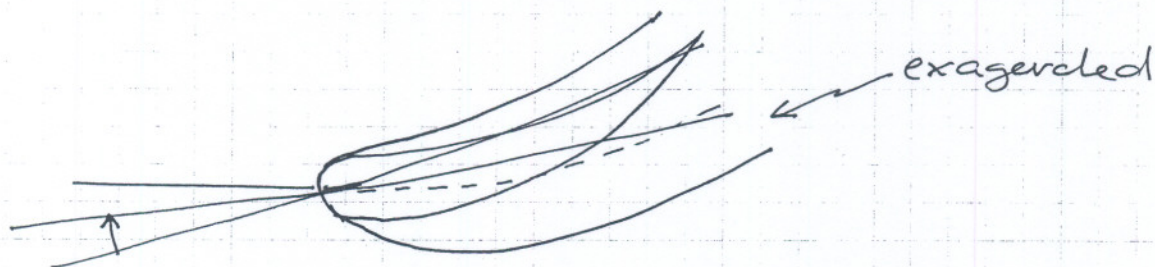
- It's very difficult to estimate the direction of V_{∞} (It is not the direction of the motion of the car)

- A more precise results can be obtained by means of the iterative procedure

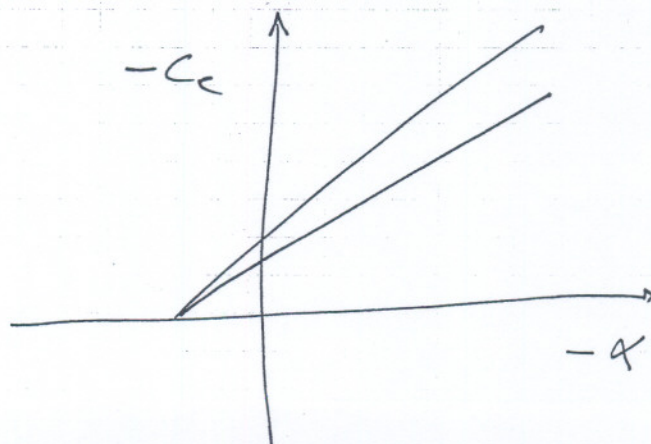


from the first calculation we obtain the pressure distribution

This allows the δ distribution to be obtained



⊗ A decrease in the angle of attack.



- Effects of different parameters

Thickness → increases max V around the profile

theoretically increase C_{ex} , but compensate for an increase in boundary layer thickness.

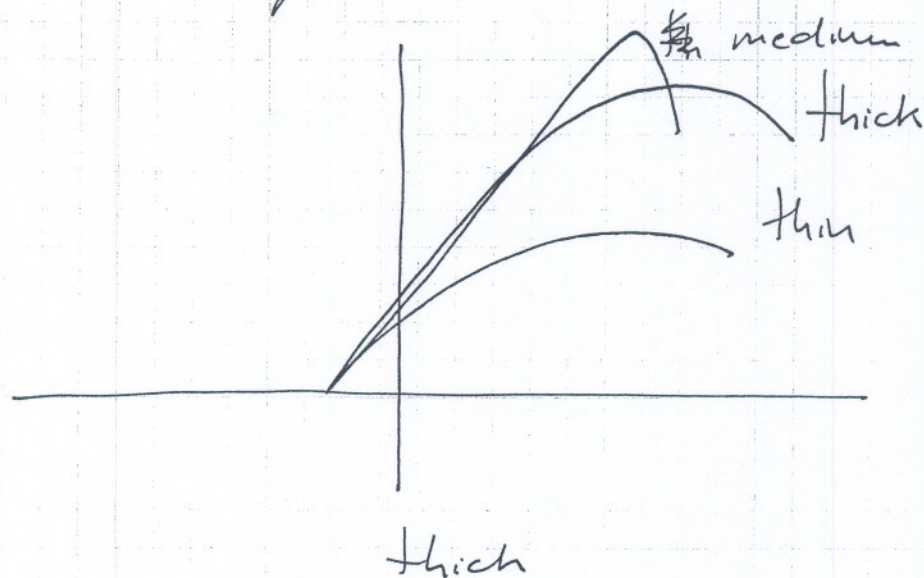
An example of correction

curvature

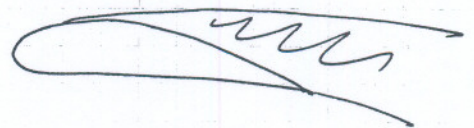
$$C_e = 2\alpha \left(1 + 0.77 \frac{t}{c} \right) \sin \alpha$$

change do

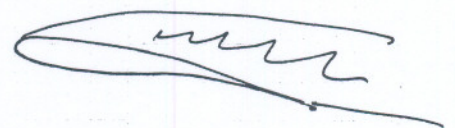
What happens when we increase the angle of attack? Separation and Stall



medium



thin



Wing

In car aerodynamics we do not need
FLAP and SLAT system

- regulation
- We can shape directly the profile at the beginning.
- Of course interaction between profiles is extensively used

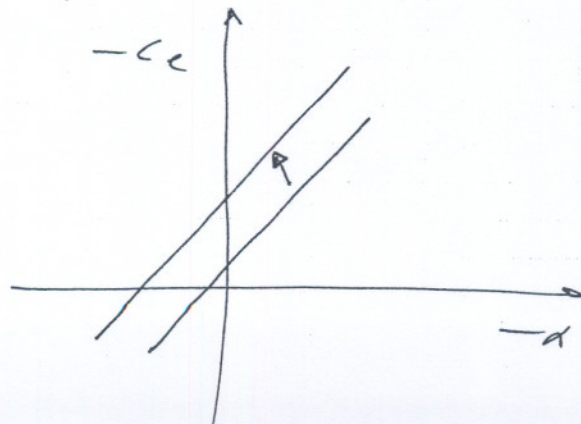


- Effects of woldew (GURNEY FLAP)



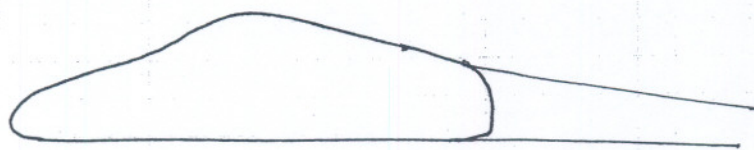
Increase in curvature

- effective at high speed
- at low speed the boundary layer bypass the strip.



Approximate procedure for separated flow

5



Separation points must be identified
A PRIORI

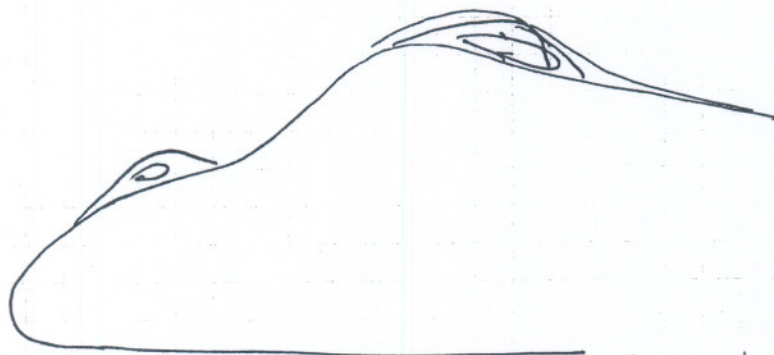
Need to model the $w \neq 0$ region

Calculate potential flow over the region $w = 0$

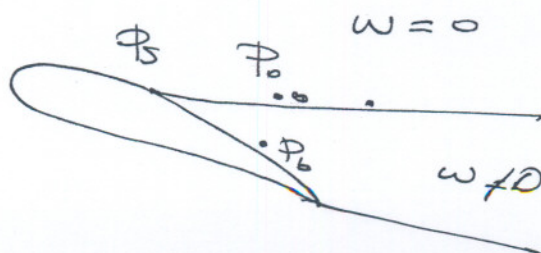
Integrate the pressure distribution on the body.

Which is the pressure that is exerted on the body?

RECIRCULATING BUBBLE



theoretically we should model the car + bubbles
then pressure remains constant.

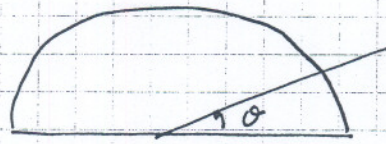


$$p_0 \neq p_b$$

p_b is more similar to p_s

A VERY SIMPLE PROBLEM. (2D)

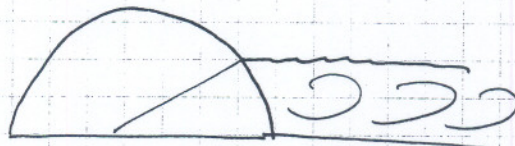
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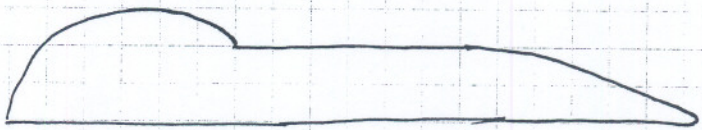
Real flow is separated

1) We need the separation point

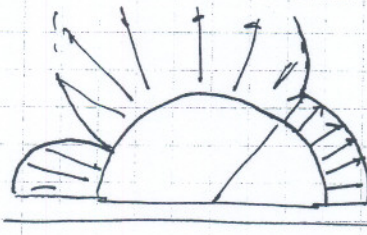
$$\theta = 40^\circ$$



In theory



Very first approximation



$$C_p = C_{ps} = 1 - \frac{V_s^2}{V_\infty^2}$$

Effect of spoiler on C_e

With this method we can estimate a FORM DRAG

Be careful!

Separation does not means decrease in LIFT