Escola d'Enginyeria de Telecomunicació i Aeroespacial de Castelldefels

Aerodynamics (AER)

LESSON 2: INVISCID FLOW
Part 1: 2D Potential Flow (Infinite Wings)

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CONTENTS

LESSON 7: 2D POTENTIAL FLOW

- Introduction
- Aerodynamic forces on an airfoil in stationary 2D potential flow:
  - D'Alembert's paradox
  - Kutta-Yukovski theorem
- Viscosity effects
- Sharp trailing edge – Streamlining
- Hypothesis of Kutta
- Generation of circulation
- Pressure, lift, drag & pitching moment coef.

2D POTENTIAL FLOW

INTRODUCTION

- **Objective** → to calculate the pressure distribution (forces *l* & *d*) on 2D airfoils moving horizontally in steady atmosphere
- **Hypotheses:**
  - long or infinite wing → 2D flow
  - *Re* >> 1 & attached Boundary Layer (BL) → viscosity effects neglected
  - *Fr* >> 1 → volume forces neglected
  - Bjerknes-Kelvin Theorem
  - properties far upwind → uniform & stationary
    } irrotational flow
  - *St* << 1 → stationary problem
  - low speed: $M < 0.30$ → compressibility effects neglected: $\rho = ct$

2D POTENTIAL FLOW

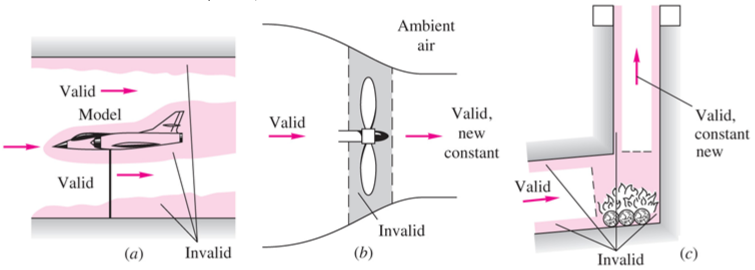
PROCEDURE TO FULFIL OBJECTIVE

To compute the aerodynamic forces (*p* distrib.) on the airfoil:

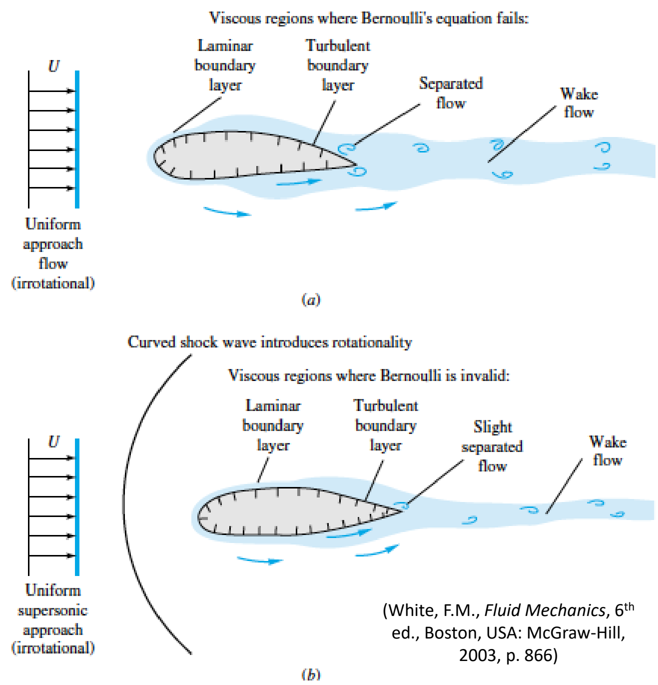
1. compute velocity potential from differential Eq. for velocity potential
2. then compute velocity field from velocity potential
3. then compute pressure field by application of Bernoulli Eq.:

$$\frac{1}{2}\rho_\infty|\nabla\Phi|^2 + p = \frac{1}{2}\rho_\infty U_\infty{}^2 + p_\infty$$

(White, F.M., *Fluid Mechanics*, 6th ed., Boston, USA: McGraw-Hill, 2003, p. 866)



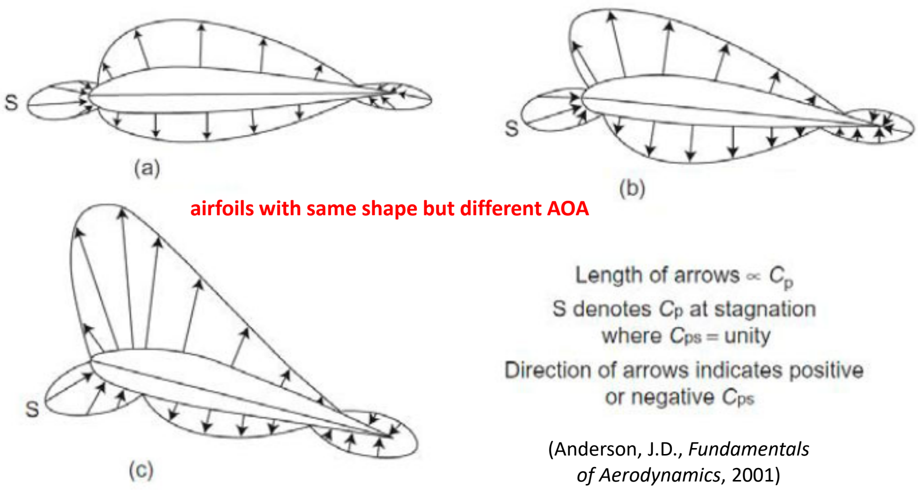
2D POTENTIAL FLOW



(White, F.M., *Fluid Mechanics*, 6th ed., Boston, USA: McGraw-Hill, 2003, p. 866)

2D POTENTIAL FLOW

PRESSURE DISTRIBUTIONS AROUND AIRFOILS (1)

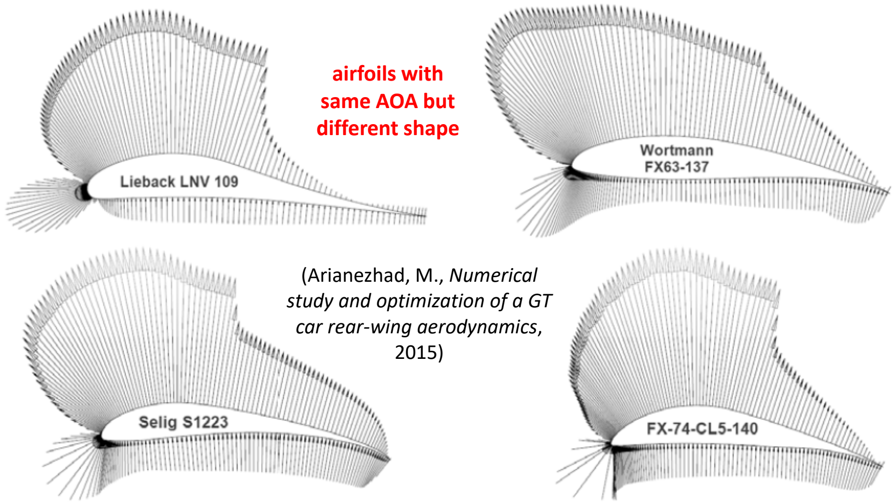


airfoils with same shape but different AOA

(Anderson, J.D., *Fundamentals of Aerodynamics*, 2001)

2D POTENTIAL FLOW

PRESSURE DISTRIBUTIONS AROUND AIRFOILS (2)



airfoils with same AOA but different shape

(Arianezhad, M., *Numerical study and optimization of a GT car rear-wing aerodynamics*, 2015)

2D POTENTIAL FLOW

FORCES ON AIRFOIL IN 2D POTENTIAL FLOW

- relate circulation Γ with Newton's 2nd Principle to calculate *lift*
- control vol. containing airfoil & with boundaries not too far from it
- Aerodynamic forces on an airfoil in stationary 2D potential flow:
  - ***x*-axis:** D'Alembert's paradox → aerodynamic drag on 2D obstacle in a stationary 2D potential flow is NULL →
  - ***z*-axis:** Kutta-Yukovski theorem →

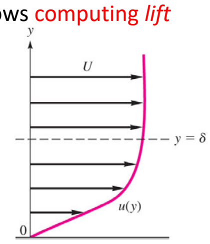
$$d = 0$$
$$l = \rho U_\infty \Gamma$$

- Conclusions:
  - **potential flow:** aerodyn. force perpendicular to incident flow (only *lift*)
  - airfoils generate *lift* only if circulation is NOT null

2D POTENTIAL FLOW

VISCOSITY EFFECTS

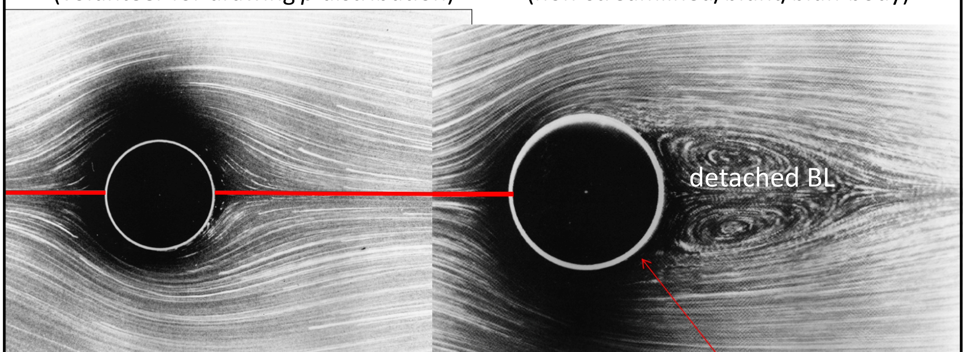
- Contradiction?
  - topic 1 → Bjerknes-Kelvin + flying in steady atmosphere → potential flow → circulation NULL!
  - previous slide → airfoils generate *lift* only if circulation is NOT NULL!
- Explanation → viscosity effects:
  - if BL thin & not detached, p distribution on airfoil due to inviscid potential flow = p distrib. due to real flow (in BL models, transversal p gradient is NULL)
  - regardless viscosity NEGLECTED, potential flow model allows computing *lift*
- Yet viscosity plays key role in:
  - flow motion around airfoil
  - generation of circulation on airfoil



2D POTENTIAL FLOW

SHARP TRAILING EDGE (1) – STREAMLINING

potential flow (volunteer for drawing p distribution) | **real flow** (non-streamlined/blunt/bluff body)



Source: Photograph by Sadatoshi Taneda, from Van Dyke, Milton, An Album of Fluid Motion, The Parabolic Press, Stanford, Calif., 1982

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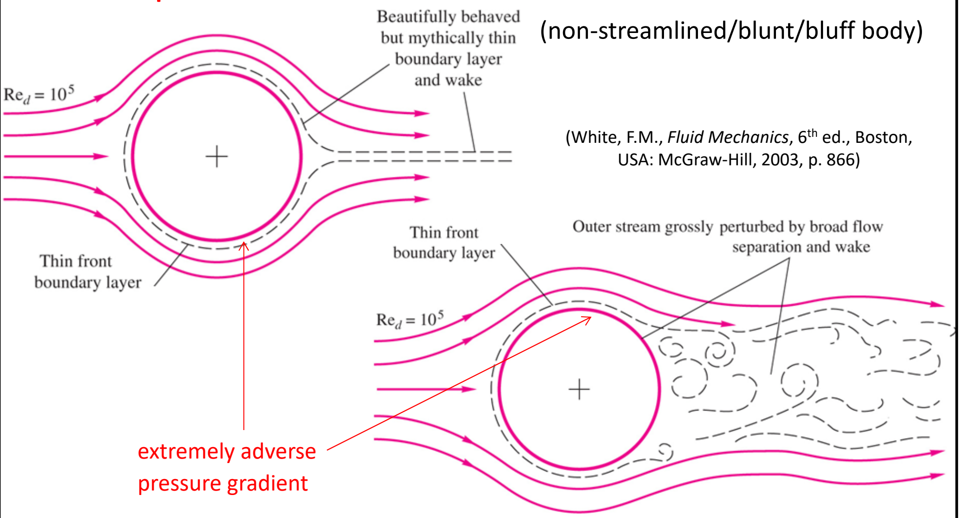
(Anderson, J.D., *Fundamentals of Aerodynamics*, 2001)

2D POTENTIAL FLOW

SHARP TRAILING EDGE (1) – STREAMLINING

potential flow | **real flow**

(non-streamlined/blunt/bluff body)



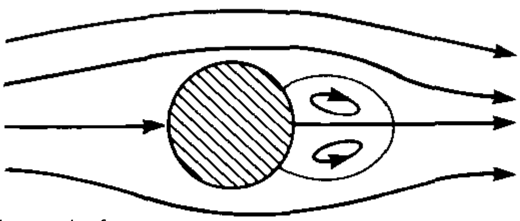
(White, F.M., *Fluid Mechanics*, 6th ed., Boston, USA: McGraw-Hill, 2003, p. 866)

2D POTENTIAL FLOW

SHARP TRAILING EDGE (2) – STREAMLINING

Consequences of detachment of BL in blunt/bluff bodies:

- NO Trailing Edge (TE) stagnation point → D'Alembert's paradox does NOT hold → wake (or pressure or form) drag aside from friction drag
- opposite-sign vortices detach from upper & lower surfaces → yet global vorticity is NULL



(Anderson, J.D., *Fundamentals of Aerodynamics*, 2001)

2D POTENTIAL FLOW

SHARP TRAILING EDGE (3) – STREAMLINING

Flow behavior around streamlined bodies: sharp trailing edge (TE):

- POTENTIAL flow → rear stagnation point in upper surf. → NOT realistic
- REAL flow → larger vorticity detached from lower surface
  → circulation appears on the airfoil:
  - opposite sign respect to detached net vorticity
  - approx. equal in absolute value
  - pushes rear stagnation point towards trailing edge

(Eleni, D.C., *J Mech Eng Res* 4(3) (2012) 100-111)

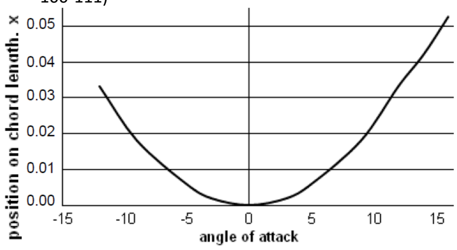
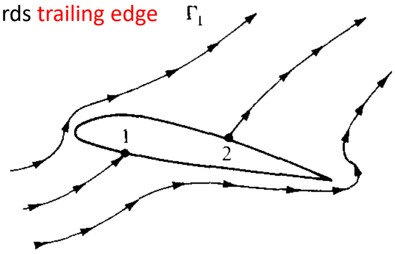


Figure 13. Stagnation point for various angles of attack.

(Anderson, J.D., *Fundamentals of Aerodynamics*, 2001)



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2D POTENTIAL FLOW

SHARP TRAILING EDGE (3) – STREAMLINING

Flow behavior around streamlined bodies: sharp trailing edge (TE):

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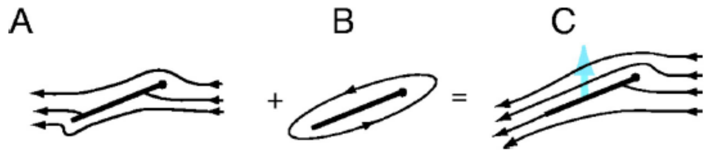
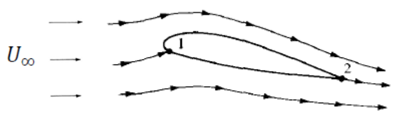


(Anderson, J.D., *Fundamentals of Aerodynamics*, 2001)



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2D POTENTIAL FLOW

HYPOTHESIS OF KUTTA (1)

- Hypothesis of Kutta: “Circulation around airfoil is such that the rear stagnation point is located in the trailing edge (or disappears)”
- Upper & lower flow meet in TE with same pressure →
  → MUST have same velocity (Bernoulli Eq.)
- 2 possibilities:
  - **angular TE:** 2 tangents → velocities can only be equal if NULL → stagnation point in TE
  - **tangential TE:** unique tangent → velocities do NOT need to be null → NO stagnation point in TE

Question: Is it correct to state that the Kutta hypothesis can only be fulfilled if the velocity of the upper and lower flow in the TE is null?

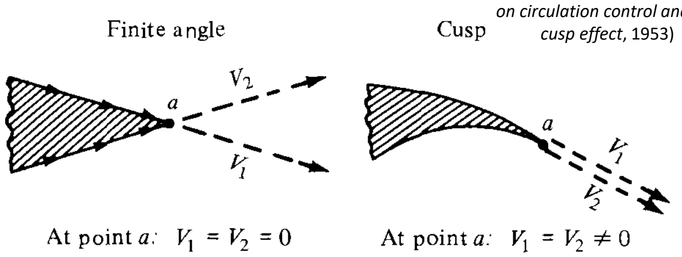
2D POTENTIAL FLOW

HYPOTHESIS OF KUTTA (2)

2 possibilities:

- **angular TE:** 2 tangents → velocities can only be equal if NULL → stagnation point in TE
- **tangential TE:** unique tangent → velocities do NOT need to be null → NO stagnation point in TE

(Hazen, D.C., *Preliminary report on circulation control and the cusp effect*, 1953)



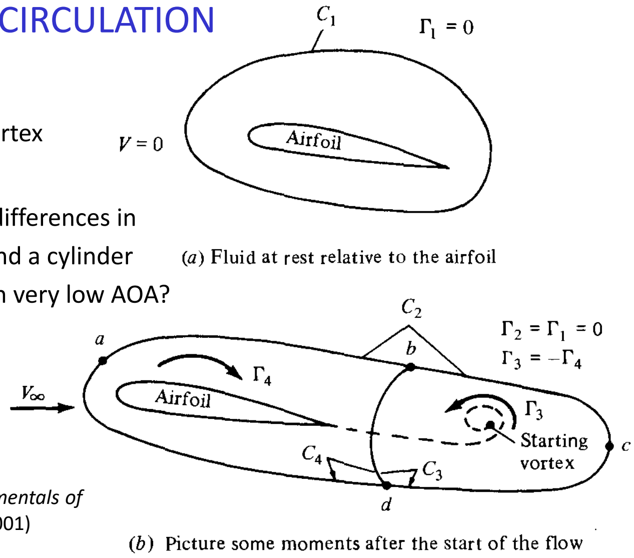
(Anderson, J.D., *Fundamentals of Aerodynamics*, 2001)

2D POTENTIAL FLOW

GENERATION OF CIRCULATION

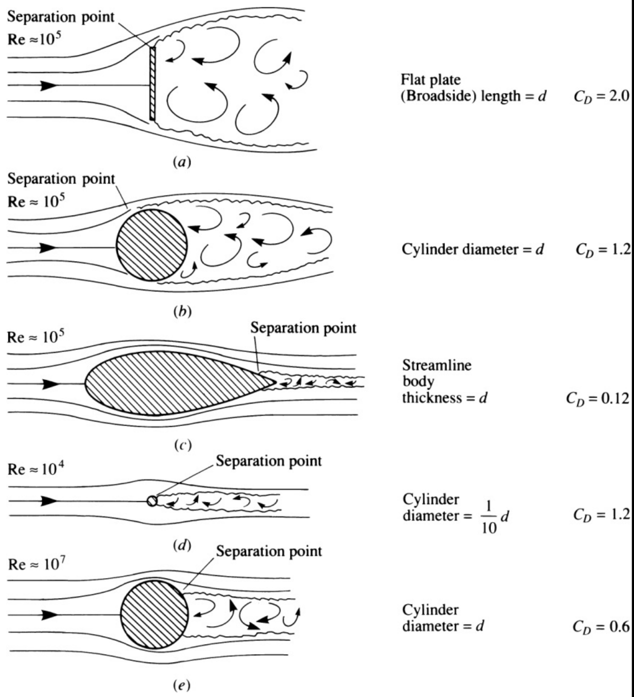
Show video of starting vortex

Question: What are the differences in behavior of air flow around a cylinder and around an airfoil with very low AOA?



(Anderson, J.D., *Fundamentals of Aerodynamics*, 2001)

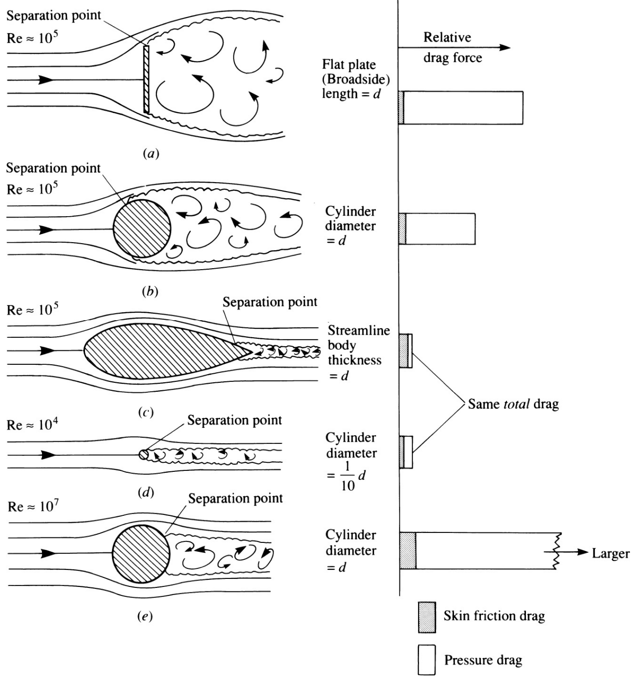
SHARP TRAILING EDGE (4) – STREAMLINING



(Anderson, J.D., *Fundamentals of Aerodynamics*, 2001)

SHARP TRAILING EDGE (5) – STREAMLINING

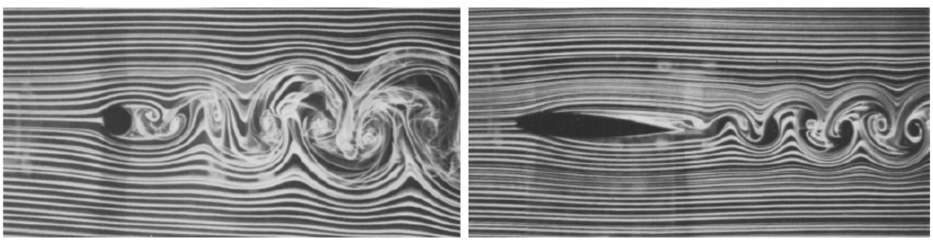
(Anderson, J.D., *Fundamentals of Aerodynamics*, 2001)



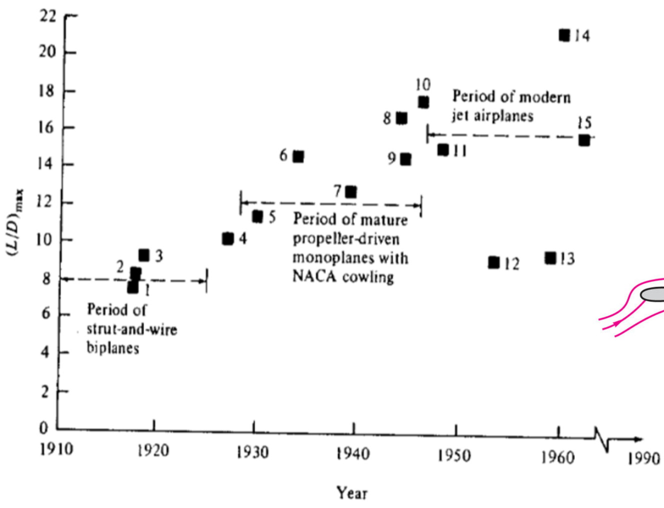
2D POTENTIAL FLOW

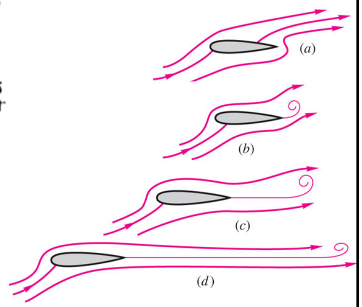
SUMMARY

- Potential flow model allows computing *p* distribution if BL attached
  → allows computing *lift* limitation: *drag* is 0! not realistic!
- even if BL attached → *drag* not null (viscosity in BL causes friction)
- streamlining very efficient → *lift* >> *drag* (e.g. *lift*/*drag* ≈ 30)



(Bienkiewicz, B., A flow visualization technique for low-speed wind-tunnel studies, 1987)





(White, F.M., *Fluid Mechanics*, 6th ed., Boston, USA: McGraw-Hill, 2003, p. 866)

Figure 6.61 Use of lift-to-drag ratio to illustrate three general periods of twentieth-century airplane design.

(Anderson, J.D., *Introduction to Flight*, 2002)

2D POTENTIAL FLOW

PRESSURE COEF. ON AIRFOIL

With p distrib. on airfoil's surface → distrib. of p coef. on airfoil:

$$c_p(x, z_p(x)) = \frac{p(x, z_p(x)) - p_\infty}{\frac{1}{2}\rho_\infty {U_\infty}^2}$$

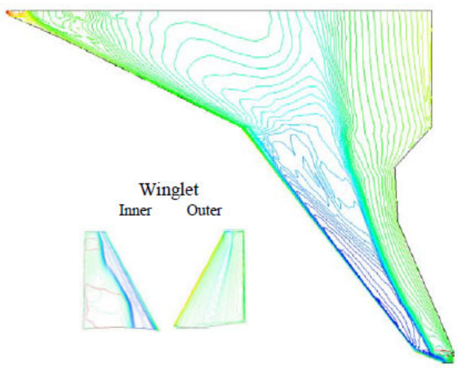


Fig. 11. Contour lines of pressure coefficient on the baseline geometry, $\alpha = 3°$, $M = 0.85$.

(Qin, N., Aerodynamic applications of blended wing body aircraft, *Progress in Aerospace Sciences* 40 (2004) 321–343)

2D POTENTIAL FLOW

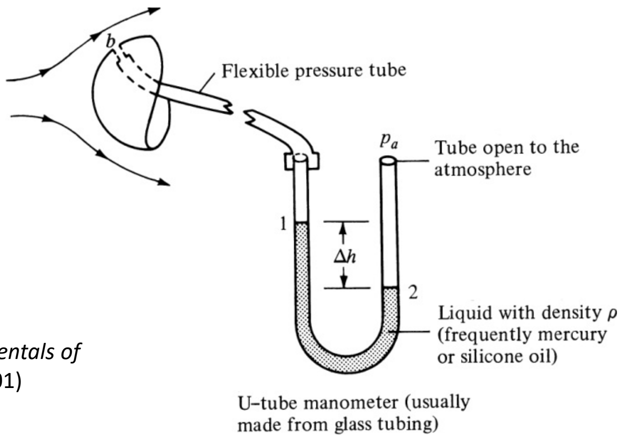
PRESSURE COEF. ALONG CHORD (1)

- instead of *p* coef. on airfoil, work with *p* coef. along chord: $c_p(x)$
- $c_p(x) \rightarrow$ projection along *z* axis of force per unit length on each point of airfoil
- it can be demonstrated that $c_p(x) = c_p(x, z_p(x)) = \dfrac{p(x, z_p(x)) - p_\infty}{\frac{1}{2}\rho_\infty {U_\infty}^2}$
- Graphically, we usually represent $-c_p(x)$
- When the flow velocity increases, so does $-c_p(x)$

2D POTENTIAL FLOW

PRESSURE COEF. ALONG CHORD (2)

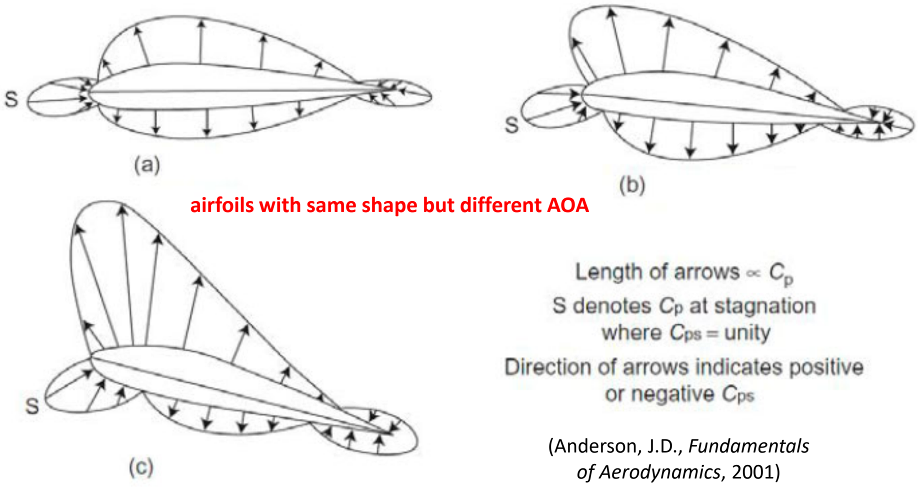
Graphically, we usually represent $-c_p(x)$



(Anderson, J.D., *Fundamentals of Aerodynamics*, 2001)

2D POTENTIAL FLOW

PRESSURE DISTRIBUTIONS AROUND AIRFOILS (1)



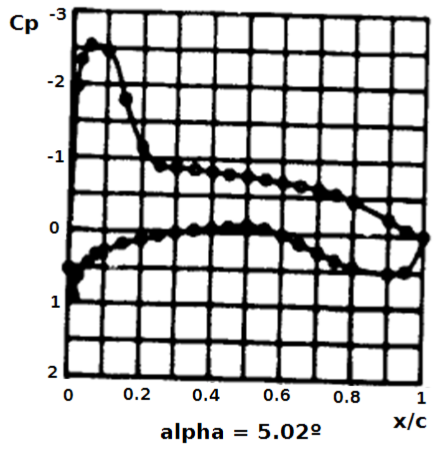
(Anderson, J.D., *Fundamentals of Aerodynamics*, 2001)

2D POTENTIAL FLOW

PRESSURE COEF. ALONG CHORD (3)

Graphically, we usually represent $-c_p(x)$

TEST	187
RUN	9
MACH	.600
Re	10.0 x 10^6



Question:
How much is the global airfoil's lift coefficient?

(Jenkins, R.V., *Aerodynamic performance & pressure distributions for NASA SC(2)-0714 airfoil*, 1988)

2D POTENTIAL FLOW

LIFT COEF. ALONG CHORD & GLOBAL LIFT COEF. (1)

Distribution of *lift* coef. along chord:

$$c_l(x) = c_{p,lower}(x) - c_{p,upper}(x)$$

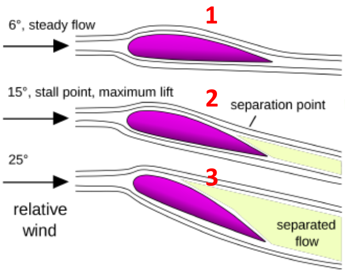
Global airfoil's *lift* coef.:

$$c_l = \frac{1}{c}\int_{x_{LE}}^{x_{TE}} c_l(x)dx$$

- for $|\alpha| << 1$ → $c = x_{TE} - x_{LE}$
- for $|\alpha| << 1$ → *lift* coef. linear with α: $c_l \propto \alpha$ (slope is constant)
- theory fails if $|\alpha|$ large:
  - as α grows/decreases → BL eventually detaches, slope starts to decrease & reaches 0 → max./min. *lift* coef.
  - if α continues to grow/decrease → slope becomes increasingly negative
    - » we say that the airfoil is in STALL
- typically, $c_{l,max} \approx 1.5$ for airfoils with no hyper-lift devices

2D POTENTIAL FLOW

GLOBAL LIFT COEF. vs. AOA



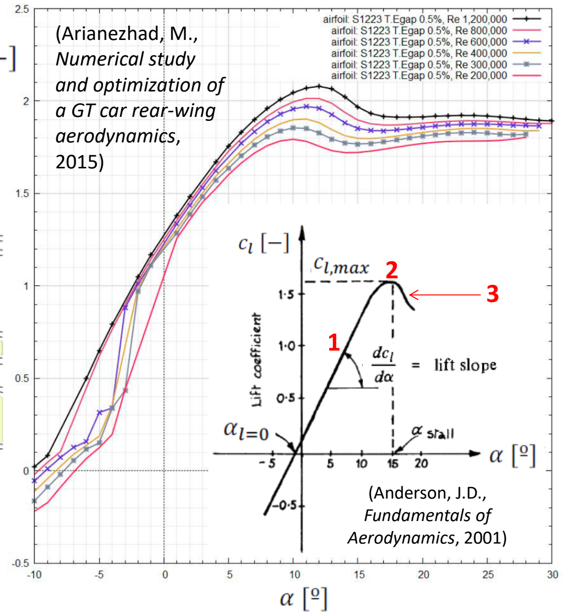
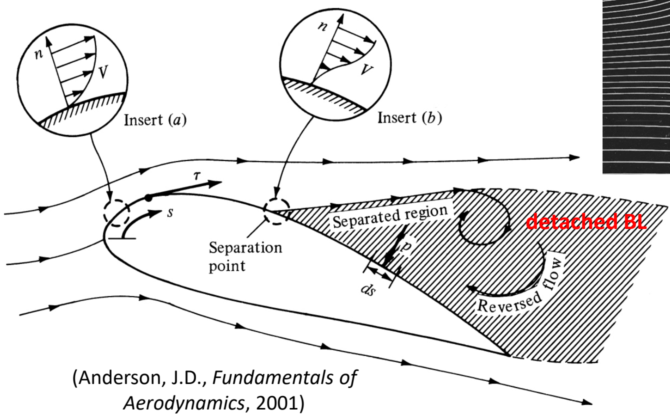


Figure 2.7: Performance comparison in different Reynolds numbers computed by XFOIL

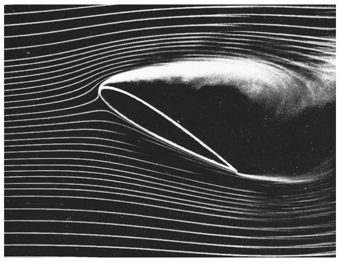
2D POTENTIAL FLOW

LIFT COEF. ALONG CHORD & GLOBAL LIFT COEF. (2)

Detachment of BL:



(Anderson, J.D., *Fundamentals of Aerodynamics*, 2001)

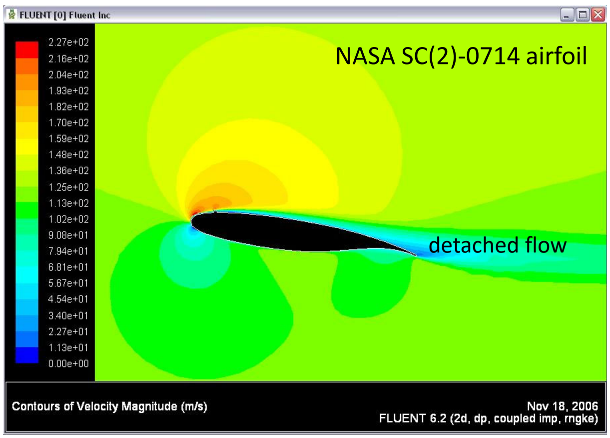


(White, F.M., *Fluid Mechanics*, 6th ed., Boston, USA: McGraw-Hill, 2003, p. 866)

2D POTENTIAL FLOW

LIFT COEF. ALONG CHORD & GLOBAL LIFT COEF. (3)

Detachment of BL:



(Rojas, J.I., 2006)

(Deng, J.-J., On exploring application of MEMS in aerodynamic flow control, *Proceedings of CANEUS Conference*, 2006, Toulouse, France)

2D POTENTIAL FLOW

LIFT COEF. ALONG CHORD & GLOBAL LIFT COEF. (4)

Global airfoil's *lift* coef.:

$$c_l = \frac{1}{c}\int_{x_{LE}}^{x_{TE}} c_l(x)dx$$

- for $|\alpha| << 1$ → *lift* coef. linear with α: $c_l \propto \alpha$
  - E.g.: Yukovsky transformation → $c_l = 2\pi \dfrac{\delta + (1+\gamma)\alpha}{1 + \dfrac{\gamma}{1+2\gamma}}$
  - E.g.: thin airfoil → $c_l = 2\pi(\delta + (1+\gamma)\alpha)$
  - E.g.: flat plate → $c_l = 2\pi\alpha$

Question: Compute the global lift coefficient for a flat plate with angle of attack (AOA) 10º. Compute the global lift coefficient for a symmetric thin airfoil.

2D POTENTIAL FLOW

FORCES ON AIRFOIL

In 2D, we compute forces per unit span [N/m]:

- *lift* → $l = \frac{1}{2}\rho U_\infty{}^2 c c_l$
- *drag* → $d = \frac{1}{2}\rho U_\infty{}^2 c c_d$

Question: Compute lift for previous plate at SL in ISA at 60 km/h, if chord is 30 cm.

Global airfoil's *aerodynamic drag* coef.: c_d

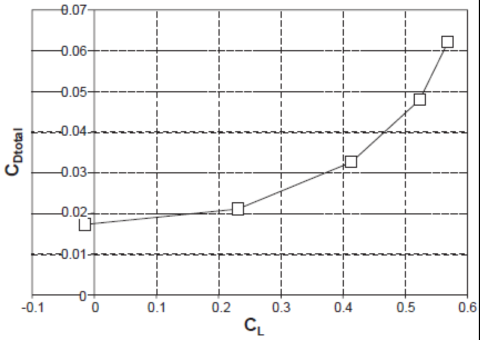
- typically, $c_{d,min} \approx 0.004$ for a laminar airfoil

2D POTENTIAL FLOW

AERDYNAMIC DRAG COEF. – POLAR CURVE

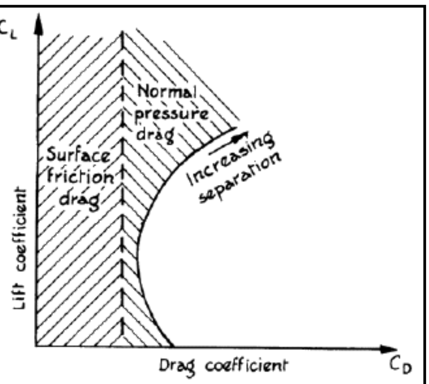
- Polar curve: relationship between *lift* & *drag* coef. → $c_d = f(c_l)$
- E.g.: laminar airfoil → laminar BL in a small range of α/*lift* coef.
- catalogues listing airfoil data:

e.g.: UIUC:
http://www.ae.uiuc.edu/m-selig/ads.html



(Qin, N., Aerodynamic applications of blended wing body aircraft, *Progress in Aerospace Sciences* 40 (2004) 321–343)

Fig. 8. Lift-drag polar for baseline geometry $M = 0.85$.



(Anderson, J.D., *Introduction to Flight*, 2002)

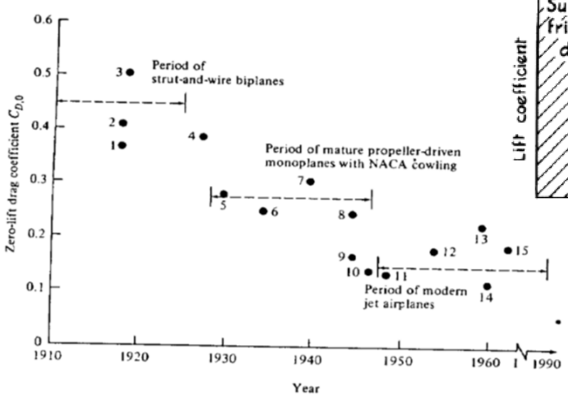


Figure 6.60 Use of zero-lift drag coefficient to illustrate three general periods of twentieth-century airplane design. The numbered data points correspond to the following aircraft: (1) SPAD XIII, (2) Fokker D-VII, (3) Curtiss JN-4H Jenny, (4) Ryan NYP (*Spirit of St. Louis*), (5) Lockheed Vega, (6) Douglas DC-3, (7) Boeing B-17, (8) Boeing B-29, (9) North American P-51, (10) Lockheed P-80, (11) North American F-86, (12) Lockheed F-104, (13) McDonnell F-4E, (14) Boeing B-52, (15) General Dynamics F-111D.

2D POTENTIAL FLOW

PITCHING MOMENT & PITCHING MOMENT COEF. (1)

- aerodynamic loading NOT fully defined by simply stating *lift & drag*
- it is necessary to provide also:
  - point of application of *lift* & *drag*; OR
  - moment produced by *lift* & *drag* in a reference point
- typical reference points:
  - pressure center (*cp*): point of application of *lift* & *drag* (moment is NULL)
  - aerodynamic center (*ca*): pitching moment coef. independent of α, for $|\alpha| << 1$
    - subsonic regime: *ca* located approx. in 25% of chord
    - supersonic regime: *ca* located approx. in 50% of chord

2D POTENTIAL FLOW

PITCHING MOMENT & PITCHING MOMENT COEF. (2)

Pitching moment coef. respect to a generic point:

$$c_{m,point} = \frac{-1}{c^2}\int_{x_{LE}}^{x_{TE}} c_l(x)\left(x - x_{point}\right)dx$$

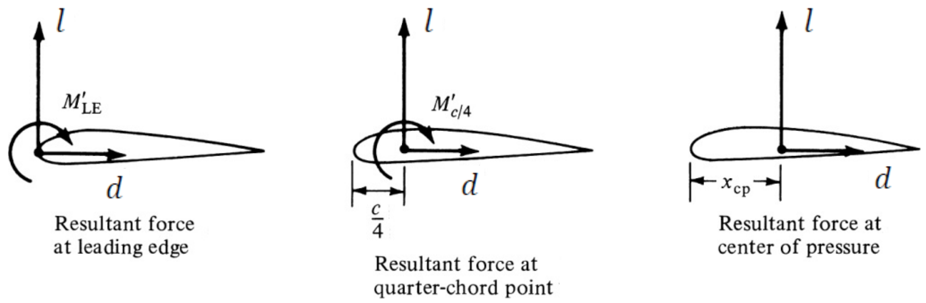
$$c_{m,2} = c_{m,1} - c_l\left(\frac{x_1}{c} - \frac{x_2}{c}\right)$$

Pitching moment respect to a generic point:

$$m_{point} = \frac{1}{2}\rho {U_\infty}^2 c^2 c_{m,point}$$

2D POTENTIAL FLOW

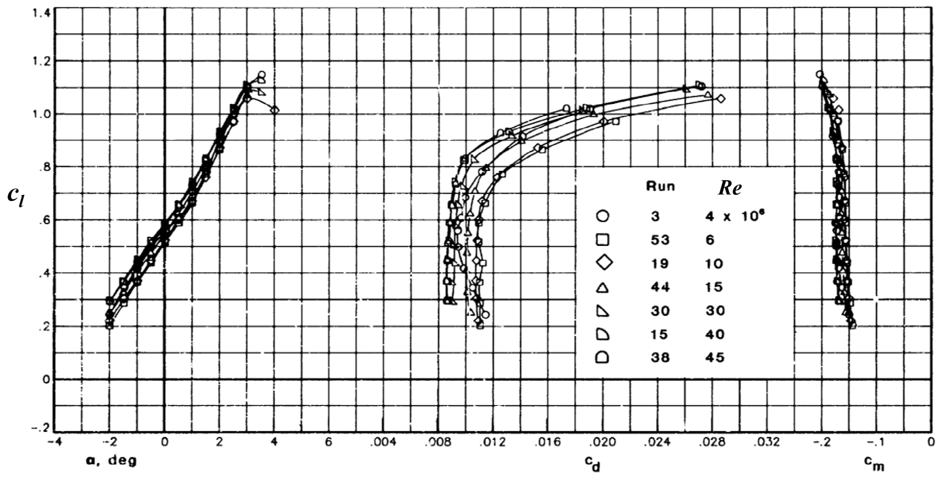
PITCHING MOMENT & PITCHING MOMENT COEF. (3)



(Anderson, J.D., *Fundamentals of Aerodynamics*, 2001)

2D POTENTIAL FLOW

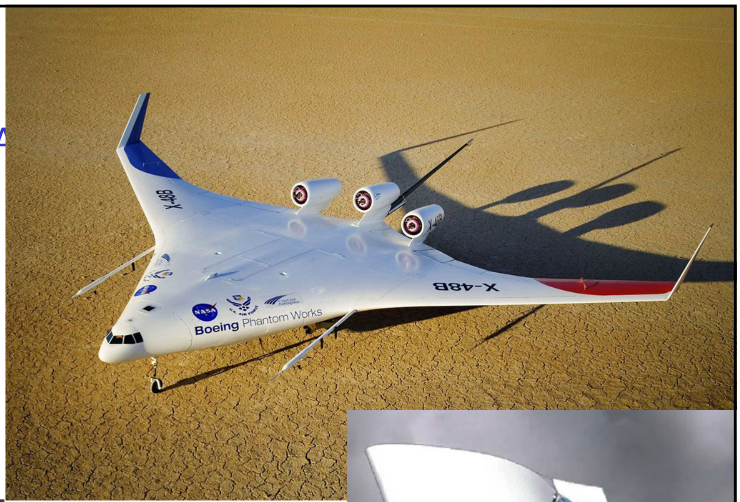
PITCHING MOMENT & PITCHING MOMENT COEF. (4)



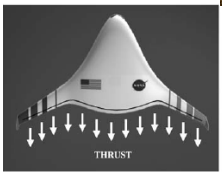
(e) $M = 0.72$

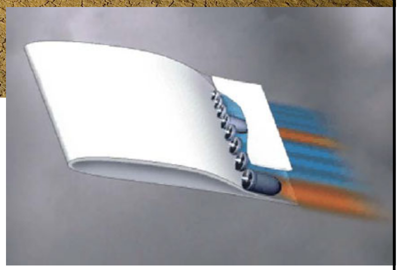
(Jenkins, R.V., *Aerodynamic performance & pressure distributions for NASA SC(2)-0714 airfoil*, 1988)

ALL WING A



(Sehra, A.K., Propulsion and power for 21st century aviation, *Progress in Aerospace Sciences* 40 (2004) 199–235)





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LESSON 2: INVISCID FLOW

Part 1: 2D Potential Flow (Infinite Wings)

THANKS FOR YOUR ATTENTION
ANY QUESTION?

(Anderson, J.D., *Fundamentals of Aerodynamics*, 2001)

CYLINDER

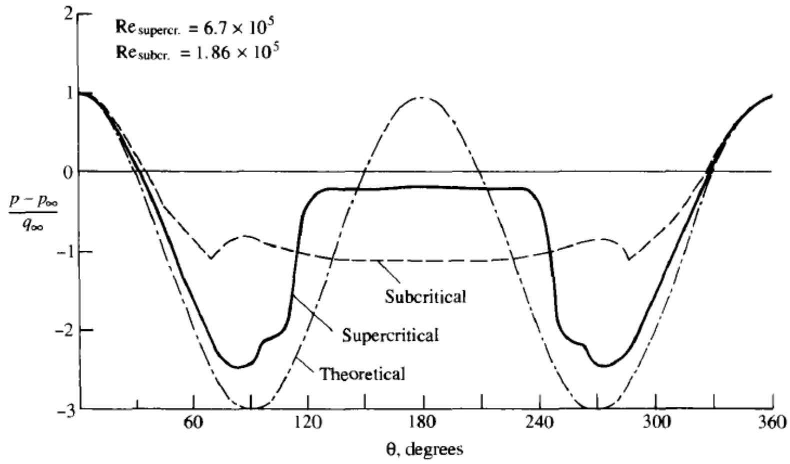


Figure 3.49 Pressure distribution over a circular cylinder in low-speed flow. Comparison of the theoretical pressure distribution with two experimental pressure distributions—one for a subcritical Re and the other for a supercritical Re.

(Anderson, J.D., *Fundamentals of Aerodynamics*, 2001)

MAGNUS EFFECT

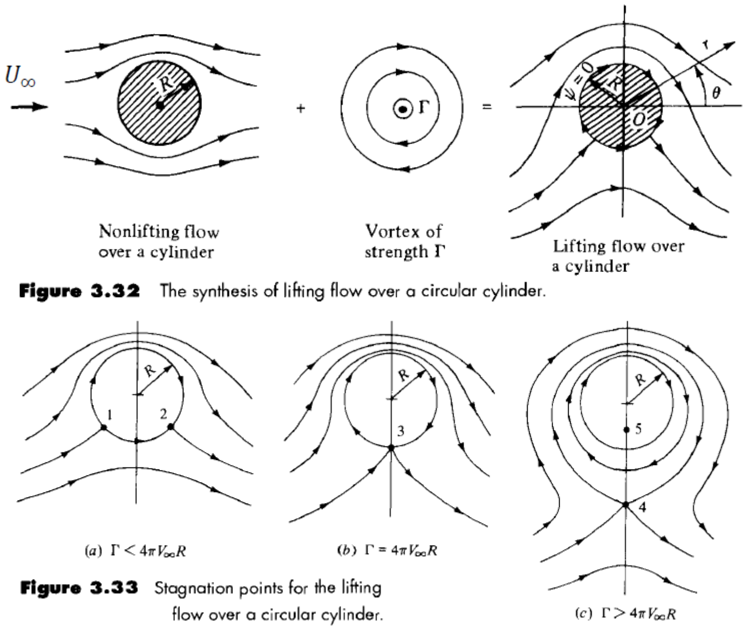
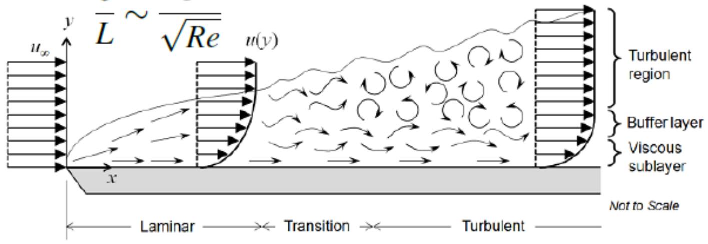


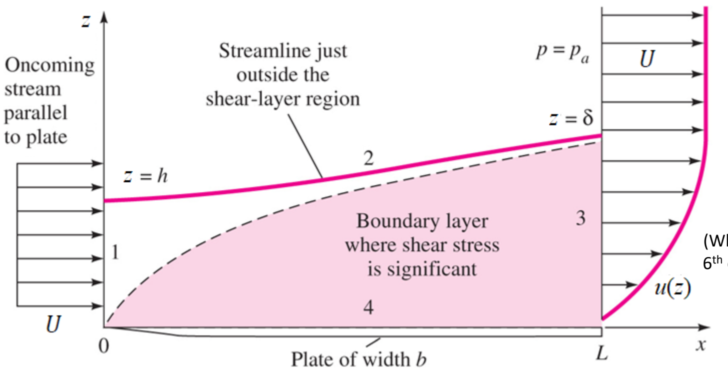
Figure 3.32 The synthesis of lifting flow over a circular cylinder.

Figure 3.33 Stagnation points for the lifting flow over a circular cylinder.

BOUNDARY LAYER

$$\frac{\delta}{L} \sim \frac{5}{\sqrt{Re}}$$





(White, F.M., *Fluid Mechanics*, 6th ed., Boston, USA: McGraw-Hill, 2003, p. 866)

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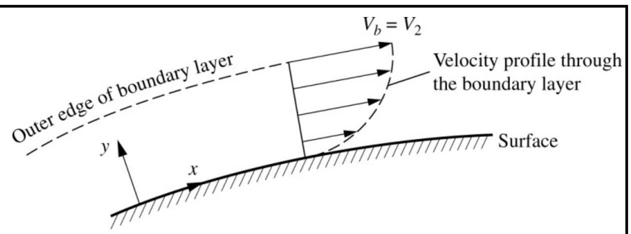
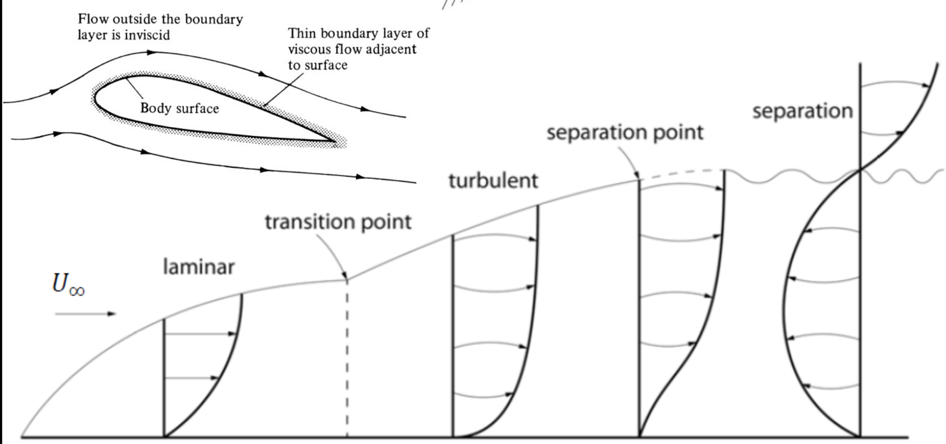
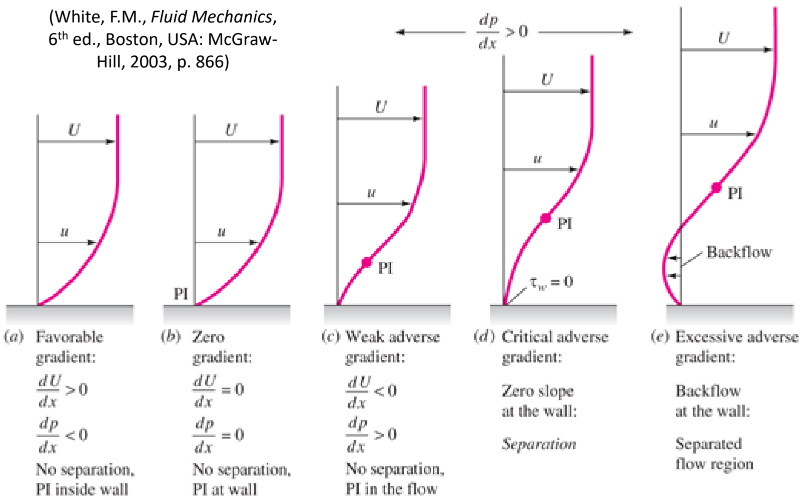
(Anderson, J.D., *Fundamentals of Aerodynamics*, 2001)





FLOW VELOCITY IN BOUNDARY LAYER

(White, F.M., *Fluid Mechanics*, 6th ed., Boston, USA: McGraw-Hill, 2003, p. 866)

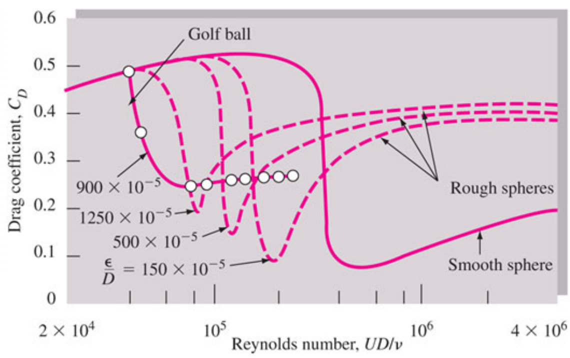


BOUNDARY LAYER

LAMINAR & TURBULENT BOUNDARY LAYER (1)

Surface of golf balls:

- characteristic length (diameter) & velocity not high → small *Re*
- plain surface → laminar BL → detaches earlier → thicker wake → *d* ↑
- carved surface → forces transition to turbulent BL → detaches later → thinner wake → *d* ↓



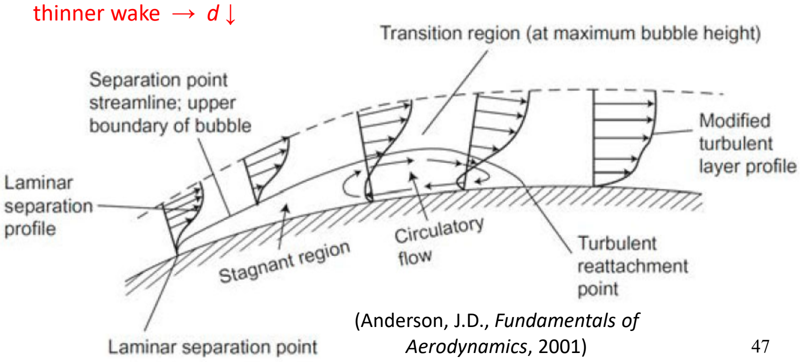
(White, F.M., *Fluid Mechanics*, 6th ed., Boston, USA: McGraw-Hill, 2003, p. 866)

BOUNDARY LAYER

LAMINAR & TURBULENT BOUNDARY LAYER (2)

Surface of golf balls:

- characteristic length (diameter) & velocity not high → small *Re*
- plain surface → laminar BL → detaches earlier → thicker wake → *d* ↑
- carved surface → forces transition to turbulent BL → detaches later → thinner wake → *d* ↓



(Anderson, J.D., *Fundamentals of Aerodynamics*, 2001)

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