Handout A1

MECH 331 Fluids I

Fall 2013

Instructor:	Prof. Tim Lee, MC 211, tim.lee@mcgill.ca
Lecture:	M W F 9:30 - 10:30, ENGMD280
Tutorial:	
Office hours:	M W F 10:35 - 11:35, MC211
Textbook:	*Introduction to Fluid Mechanics*, Fox, Pritchard and McDonald, 7th Ed.
T.A.:	Ying Y. Su (ying.su@mail.mcgill.ca); MD162

COURSE CONTENTS

Introduction and fundamental concepts	(Chapters 1 & 2)
Basic equations in integral form for a control volume	(Chapter 4)
Fluid statics	(Chapter 3)
Introduction to differential analysis of fluid motion	(Chapter 5)
Incompressible inviscid flow	(Chapter 6)
Dimensional analysis and similitude	(Chapter 7)
Internal incompressible viscous flow	(Chapter 8)
External incompressible viscous flow	(Chapter 9)
Fluid machinery	(Chapter 10; tentative)

Q/A EXERCISE

A part of class time will be used to practice problem solving skills with peer and instructor interaction. During these sessions a problem will be assigned to the entire class. You will be asked for inputs for the solution.

GRADING POLICY

HANDOUTS A1 + A2

Homework assignments (not collected)		
Midterm 1	(9:30-10:30, Monday, Oct. 7, closed books/note)	25%
Midterm 2	(9:30-10:30, Monday, Nov. 11, closed books/note)	25%
Final exam*	(3-hour exam)	50% or 75%

*Students are allowed to drop one midterm and make final 75% (a maximum).

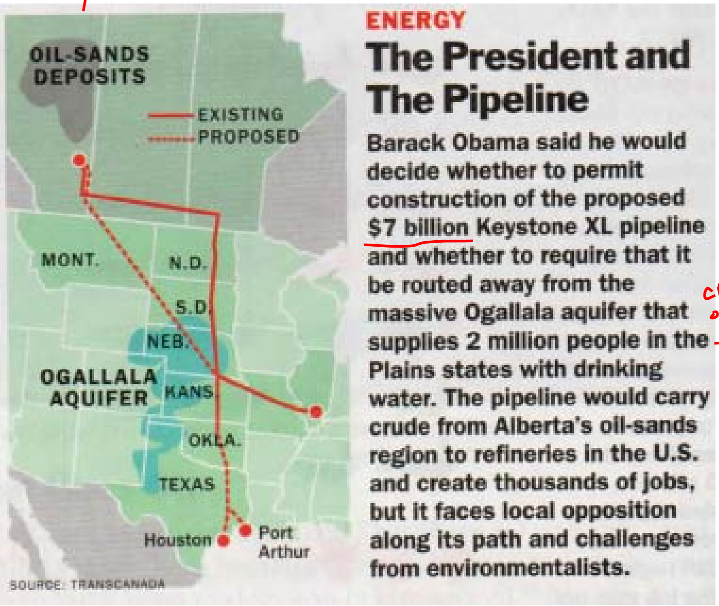
Scope and application of fluid mechanics

SUBSONIC & SUPERSONIC

- Aerodynamics of airplanes and road vehicles
- Design of fluid systems and devices
- Aerodynamics of sports
- Bioengineering
- Others

GOLF BALL
BASEBALL

E.G.,



ENERGY

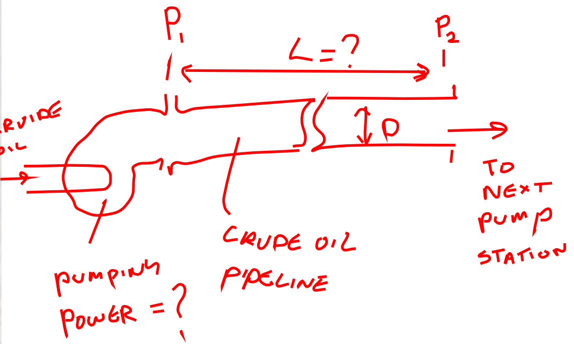
The President and The Pipeline

Barack Obama said he would decide whether to permit construction of the proposed $7 billion Keystone XL pipeline and whether to require that it be routed away from the massive Ogallala aquifer that supplies 2 million people in the Plains states with drinking water. The pipeline would carry crude from Alberta's oil-sands region to refineries in the U.S. and create thousands of jobs, but it faces local opposition along its path and challenges from environmentalists.

TIME November 14, 2011

2,148 mi LONG, D = 36" DIA.

590,000 BPD



FROM CHAP. 8 INT. INCOMP. VISCOUS FLOW

1 BARREL = 42 GALLONS

1 GALLON = 3.78 LITERS

ρ = CONST. T = CONST

The most significant basic equations in MECH 331 (incompressible and isothermal flow)

1. Reynolds Transport Theorem (integral form of $\sum \vec{F} = m\frac{d\vec{V}}{dt}$)

The sum of all forces acting on a system	=	The rate of change of momentum inside a control volume	+	The net rate of flux of momentum out through the control surface
$\sum \vec{F} = \underbrace{\sum \vec{F}_{surface}}_{\text{PRESSURE FORCE} + \text{VISCOUS FORCE}} + \sum \vec{F}_{body}$		$\frac{\partial}{\partial t}\int_{CV} \vec{V}\rho d\forall$		$\int_{CS} \vec{V}\rho\vec{V}\cdot d\vec{A}$

$\vec{V} = u\hat{i} + v\hat{j} + w\hat{k} = \vec{V}(x,y,z,t)$

2. Navier-Stokes equations (differential form of $\sum \vec{F} = m\frac{d\vec{V}}{dt}$)

The sum of all forces acting on a fluid particle	=	Pressure force acts on a fluid particle per unit volume	+	Body force acts acts on a fluid particle per $d\forall$	+	Viscous force acts on a fluid particle per unit volume
$\rho\frac{D\vec{V}}{Dt}d\forall$		$-\nabla P d\forall$		$\rho\vec{g}d\forall$		$\mu\nabla^2\vec{V}d\forall$

$d\forall = dx\,dy\,dz$

$\nabla = \frac{\partial}{\partial x} + \frac{\partial}{\partial y} + \frac{\partial}{\partial z}$

μ = FLUID VISCOSITY

$\nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}$

= DEL OPERATOR

3. Bernoulli equation (for non-viscous flow)

$$\frac{P}{\rho} + \frac{V^2}{2} + gz = \text{Constant}$$

$\therefore$ IF $\Delta z \sim 0$

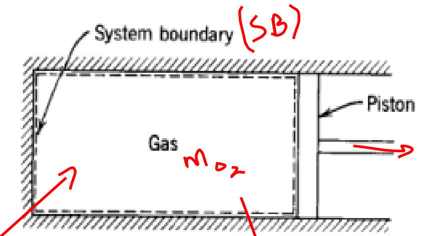
THEN ↑ IN P IS ACCOMPANIED BY ↓ IN V

VICE VERSA

Method of motion analysis

System approach

- A system is defined as a fixed, identifiable quantity of mass.
- System boundary separates the system from the surrounding (SB)
- No $\dot{m}$ crosses the system boundary



Q_{12}
"+" if added to system

W_{12}
"+"

Given: $P_1 = P_2$, $T_1 \neq T_2$, m_{0_2}, $P = \rho R T$

Find: Q_{12}

Soln:

$$Q_{12} - W_{12} = m C_v (T_2 - T_1)$$

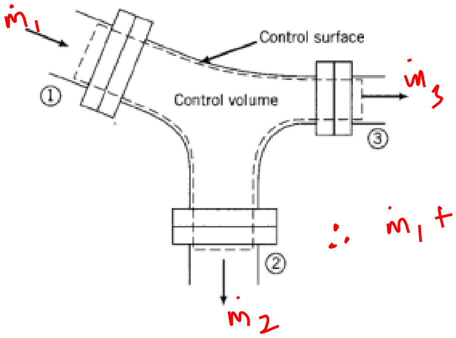
$$\int_{V_1}^{V_2} p\,dV = P \Delta V = m R \Delta T$$

$$R = C_p - C_v$$

$$\therefore Q_{12} = m C_p (T_2 - T_1)$$

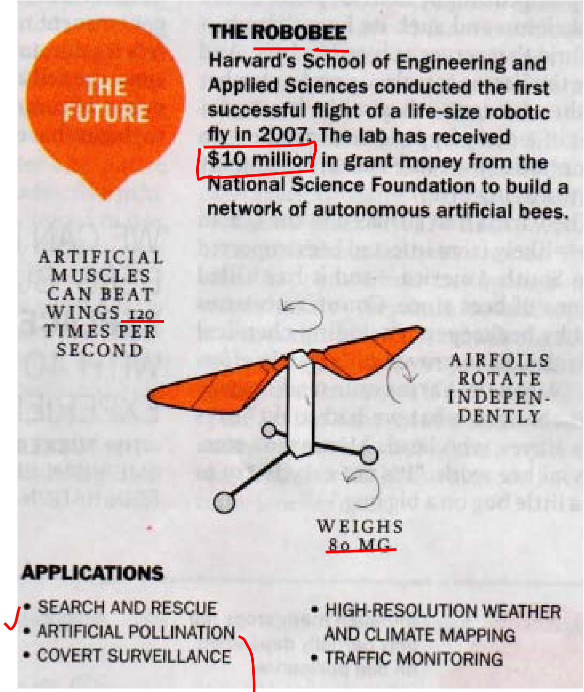
Control volume approach

- A control volume is defined as an arbitrary volume in space through which the fluid flows.
- Control surfaces are the geometric boundary of the control volume. (CS)
  Control surface can be at rest or in motion.
  Control surface can be real or imaginary
- Advantages and drawbacks over the system approach



$$\therefore \dot{m}_1 + \dot{m}_2 + \dot{m}_3 = 0$$

Some icebreaking Q/As and fundamental concepts



THE FUTURE

THE ROBOBEE

Harvard's School of Engineering and Applied Sciences conducted the first successful flight of a life-size robotic fly in 2007. The lab has received $10 million in grant money from the National Science Foundation to build a network of autonomous artificial bees.

ARTIFICIAL MUSCLES CAN BEAT WINGS 120 TIMES PER SECOND

AIRFOILS ROTATE INDEPENDENTLY

WEIGHS 80 MG

APPLICATIONS

- ✓ SEARCH AND RESCUE
- ARTIFICIAL POLLINATION
- COVERT SURVEILLANCE
- HIGH-RESOLUTION WEATHER AND CLIMATE MAPPING
- TRAFFIC MONITORING

Time (Aug 19, 2013)

∵ MASS BEE DEATH

HONEY BEE

~ 120 WING BEATS/s

FLAPPING WINGS

GENERATE

LIFT

THRUST

Hummingbird NAV

↳ DARPA $4M PROGRAM

AeroVironment Hummingbird (2011) with landing gear

Aerovironment Hummingbird displaying its maneuverability: $b = 19$ cm, $W_{total} = 19$ g, $V = 11$ mph, Duration ~ 11 minutes.

$15,000 EACH

$300,000 UAS

H-P FLAPPING-WING AIRCRAFT

"Snowbird" Human-Powered Ornithopter (HPO)

D_i D_p $D_{PARASITE}$

$D_{TOTAL} = 13.9 + 19.6 + 20.5 = 54\,N$

AUG. 2, 2010

19.3 SEC
25.6 KM/H

$W_{TO} = 43.5 + 70.8$ kg

W_e W_{PILOT}

$b = 32\,m$

$f = 0.65\,Hz$

$P_{FLIGHT} = 600\,W$

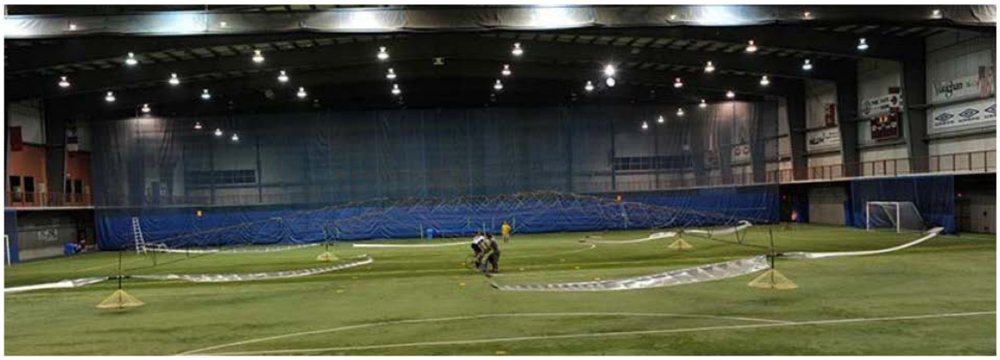
$AR = \frac{b^2}{S} = 35$

$\frac{L}{D} = 20.7$

"Atlas" Human-Powered Helicopter (HPH)

$250,000
SIKORSKI
PRIZE

$\phi\ 66.2'$



JULY, 2013

$W_e = 122$ lb

ALOFT 65 SEC

ALTITUDE 3.3 m

WITHIN 10-m BOX

P 1.1 kW → 600 W

HOW TO ESTIMATE
THE POWER REQ ??

FROM CHAPT. 4
CONTROL-VOLUME MOTION
ANALYSIS.

Q/A: WHAT IS FLAPPING WING ?

Q/A: HOW FLAPPING WINGS GENERATE LIFT & THRUST ?

Q/A: ADVANTAGES/SHORTCOMINGS OVER FIXED-WING FLIGHT ?

TF-X: Terrafugia's four-passenger, hybrid-electric roadable aircraft

Terrafugia's four-passenger, hybrid-electric automobile

TILTROTOR

In takeoff or landing mode, the TF-X is a stop/fold tiltrotor with two 600-hp electric motors in nacelles at the tips of the wings.

In flight mode, the TF-X uses a 300-hp ducted fan for thrust, giving a non-stop range of 500 mi.

U_c = 200 pmh

RANGE 500 mi

$< 19{,}000\ lb_f$

Terrafugia Transition: A light sport roadable aircraft

Automobile configuration

Airplane configuration

b = 26′6″

U_c = 105 mph

RANGE = 490 mi

TO LENGTH = 1,700′

$\overline{W}_{TO}$ = 1,430 kg

APRIL, 2012 (8 min @ 1,400′)

$ 279,000 EACH

Bell-Boing V-22 Osprey

"FLY LIKE A BIRD, HOVER LIKE A BEE."

FIXED-WING AIRCRAFT

HELICOPTER

TURBOSHAFT

6,150 SHP EACH

SPEED

RANGE

PAYLOAD

ROTOR DIA. $\phi 38'$

TILTS 97° IN 30 SEC

$W_{TO} = 60{,}500 \text{ lb}_f$

$U_c \sim 300$ mph

24 - 30 TROOPS

RANGE 1,100 mi

~ $40B R&D COSTS

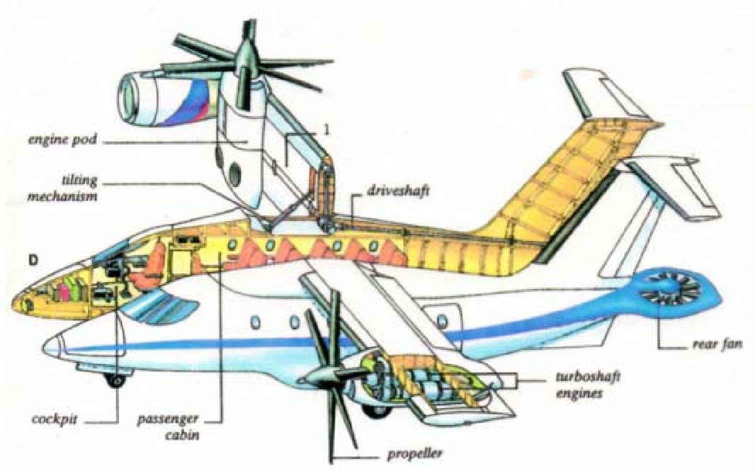
Q/A: Advantages and drawbacks of V-22 aircraft?

Q/A: Advantages and disadvantages over tiltwing aircraft?

Q/A: V-22 compared to Bell V-280 Valor tiltrotor concept

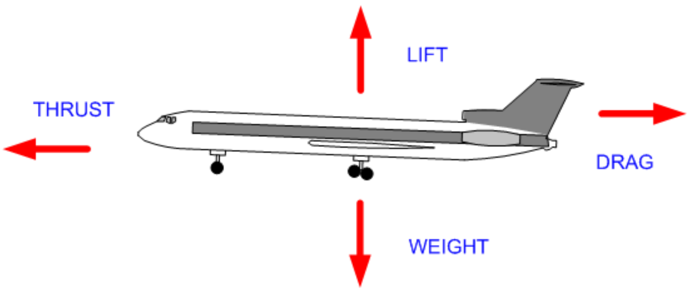
Tiltwing aircraft

ADVANTAGES ?
DISADVANTAGES ?

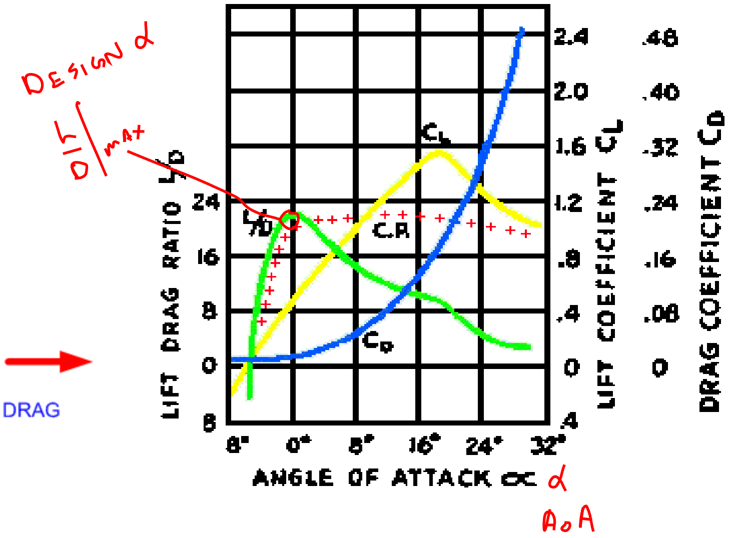


BA 609

Graphical representation of lift, drag, thrust and weight



Forces of flight



C_L, C_D and L/D versus α curves

$$C_L = \frac{L}{\frac{1}{2}\rho_\infty U_\infty{}^2 S} = \text{Lift coefficient}$$

$$C_D = \frac{D}{\frac{1}{2}\rho_\infty U_\infty{}^2 S} = \text{Drag coefficient}$$

$$\frac{L}{D} = \frac{C_L}{C_D} = \text{Lift-to-drag ratio}$$

where L = lift

D = drag

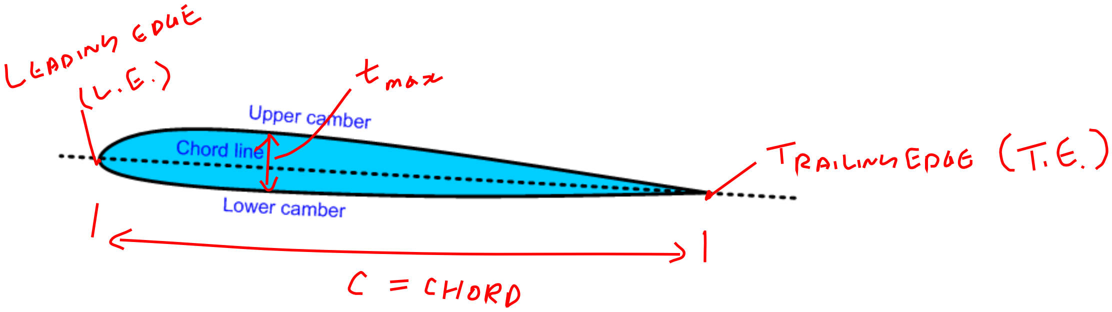
ρ_∞ = freestream density

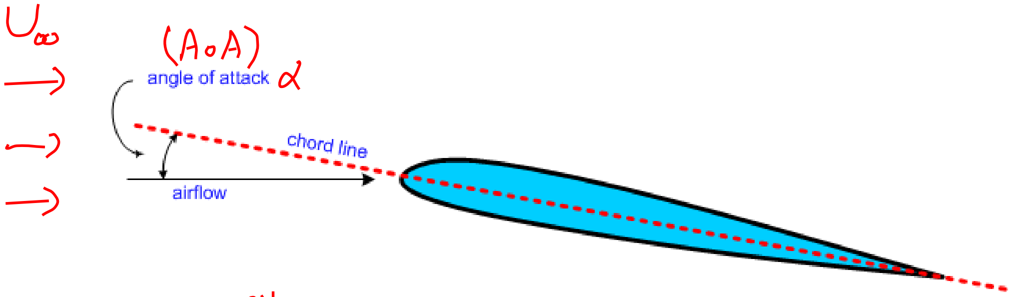
U_∞ = freestream velocity

S = wing area

$\frac{1}{2}\rho_\infty U_\infty{}^2 = P_{\text{dynamic pressure}}$

Airfoil and Angle of attack



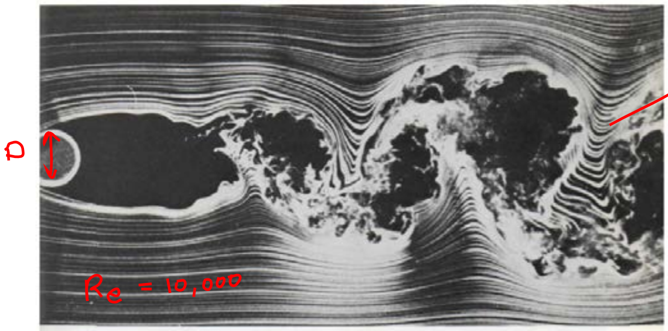


ADVISORY
AEROSPACE
NACA 0012 AIRFOIL : Symm. WITH $t_{max} = 12\%c$
NATIONAL
COMMITTEE

max CAMBER POSITION @ 40%c
NACA 2412
MAX CAMBER = 2%c

NACA 24012
max CAMBER POSITION @ $\frac{40}{2}\%c$
DESIGN $C_l = 2 \times \frac{3}{20} = 0.3$

Viscous flow around a stationary circular cylinder



TURBULENT VORTICAL WAKE

48. Circular cylinder at $R=10{,}000$**.** At five times the speed of the photograph at the top of the page, the flow pattern is scarcely changed. The drag coefficient consequently remains almost constant in the range of Reynolds number spanned by these two photographs. It drops later when, as in figure 57, the boundary layer becomes turbulent at separation. *Photograph by Thomas Corke and Hassan Nagib*

$$C_D = \frac{F_D}{\frac{1}{2}\rho_\infty U_\infty{}^2 A_p} = \text{drag coefficient}; \quad A_p = \text{projected area} = DL, \quad L = \text{cylinder length}$$

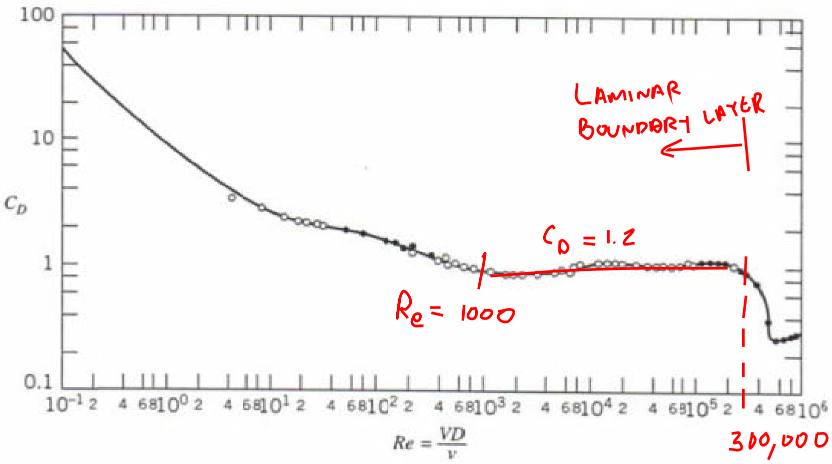
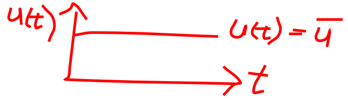


Fig. 9.13 Drag coefficient for a smooth circular cylinder as a function of Reynolds number [3].

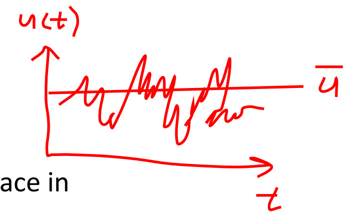
Laminar flow: Flow structure is characterized by motion in smooth layers. No $\underline{\dot{m}}$ or $\underline{\dot{m}\vec{V}}$ exchange between layers.

MASS FLOW RATE

RATE OF MOMENTUM EXCHANG



Turbulent flow: Flow structure is characterized by random, 3-D velocity fluctuations superimposed on the mean motion. For example, $u(t) = \bar{u} + u'(t)$.



Boundary layer: A thin layer of fluid in direct contact with or adjacent to the solid surface in which the viscosity effects of the shear stress $\tau_{xy} = \mu \frac{du}{dy}$ is nonzero.

Reynolds number (for viscous or real flow only)

- $$\mathrm{Re} = \frac{Fluid-inertial-force}{viscous-force} = \frac{\rho_\infty U_\infty D}{\mu} \quad \text{or} \quad \frac{\rho_\infty U_\infty C}{\mu} \quad \text{or} \quad \frac{\rho_\infty U_\infty x}{\mu}$$

  DIA. AIRFOIL CHORD STREAMWISE DISTANCE / LENGTH

  D, C and x ≡ characteristic length (of the object)

  ρ_∞ ≡ fluid density

  U_∞ ≡ fluid velocity or freestream velocity

  μ ≡ absolute viscosity of fluid

  LAMINAR OR TURBULENT

- Re is an indication of the state of the flow or boundary layer.

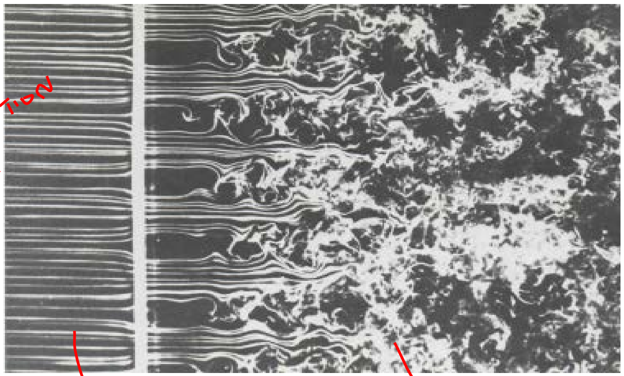
- As Re approach ∞ (or very large), the flow can be treated as inviscid (i.e., $\mu = 0$ or ideal flow).

- For incompressible flow (i.e. $M = \frac{U}{c}$ = Mach number $\le$ 0.3, where c is the speed of sound),

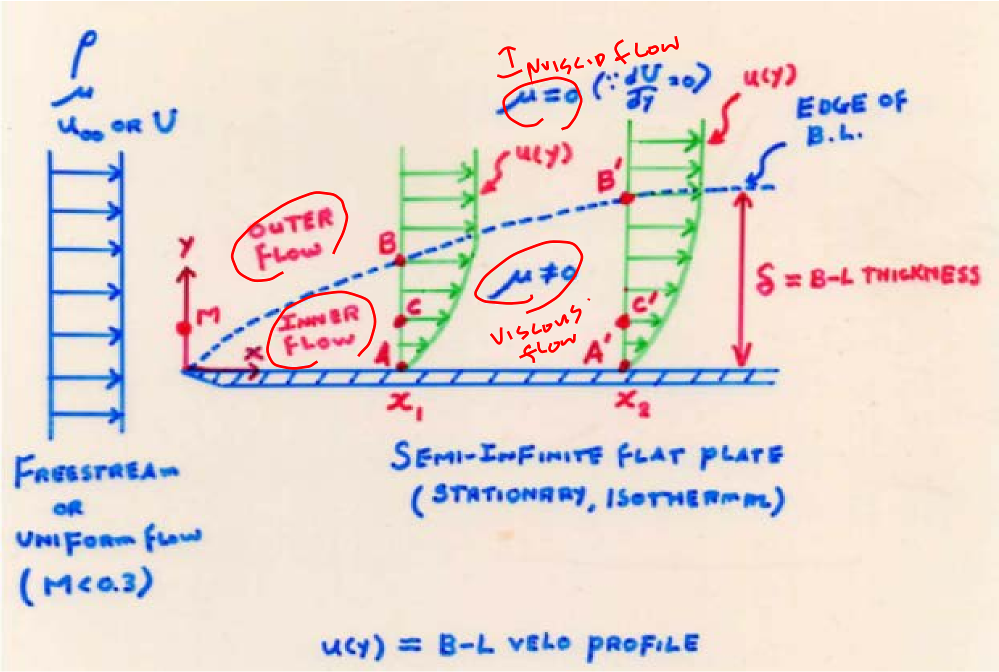
$\nu = \frac{\mu}{\rho}$ = kinematic viscosity

MECH 331 → INCOMPRESSIBLE
ISOTHERMAL FLOW

Laminar and turbulent flows over a stationary flat plate



Conceptual sketch of flat-plate boundary-layer flow



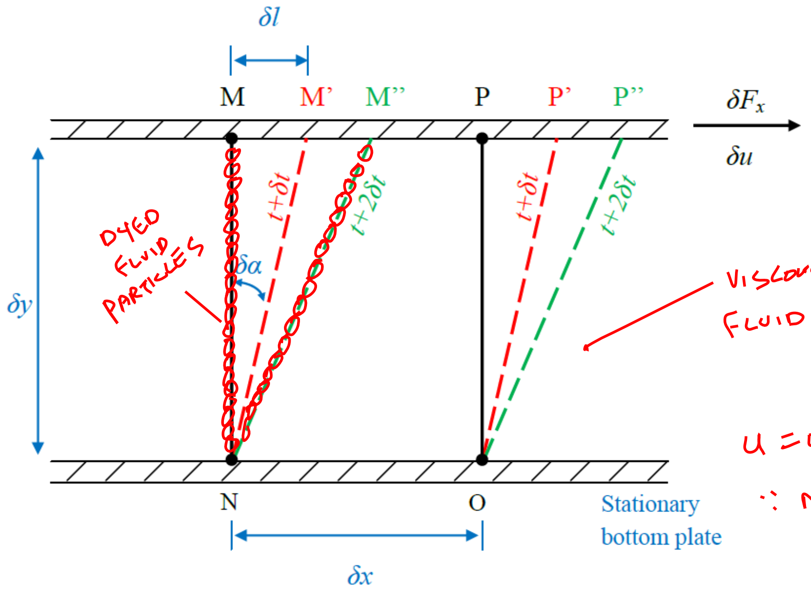
Q/A: WHY FLOW IS INVISCID FOR $y > \delta$?

Q/A: IS THE E.O.B.L. A STREAMLINE ?

RATE OF DEFORMATION

The Newton's law of viscosity (relate $\frac{d\alpha}{dt}$ to $\frac{du}{\underbrace{dy}}$)

VELO GRADIENT



$\delta\alpha$ = FLUID DEF.

$u = 0$ @ N & O

∵ NO-SLIP BOUNDARY CONDITION

∵ $\tau_{yx} = \lim_{\delta A_y \to 0} \frac{\delta F_x}{\delta A_y} = \frac{dF_x}{dA_y}$ and Deformation rate $= \lim_{\delta t \to 0} \frac{\delta \alpha}{\delta t} = \frac{d\alpha}{dt} = \frac{du}{dy}$

where $\delta l = du\,dt = dy\,d\alpha$ (for small angles)

∴ $\tau_{yx} = \mu \frac{du}{dy}$ where μ ≡ coefficient of viscous resistance = absolute viscosity

Also, $\nu = \frac{\mu}{\rho}$ = kinematic viscosity (for incompressible flow)

Timeline: A line connects adjacent "marked or dyed" fluid particles at a given time instant in a flow field.

Important notes

[1] $\mu_{\text{air @ 20C}} = 1.81 \times 10^{-5}$ N-s/m^2 and $\mu_{\text{water @ 20C}} = 1.01 \times 10^{-3}$ N-s/m^2

[2] Newtonian fluids: $\tau_{yx} = \mu \dfrac{du}{dy}$ E.g., AIR, WATER, KEROSCENE

[3] Non-Newtonian fluids: $\tau_{yx} = \kappa\left(\dfrac{du}{dy}\right)^n$ where $\kappa \equiv$ consistency index E.g., BLOOD FLOW, TOOTHPASTE

$n \equiv$ flow behavior index

REAL FLOW

[4] Viscous flow (for $\mu \neq 0$) and inviscid flow (for $\mu = 0$)

IDEAL | PERFECT FLOW

[5] All fluids possess viscosity.

[6] Definition of a fluid: A substance that deforms continuously under the application of a shear (tangential) stress τ_{yx} no matter how small the shear stress may be.

[7] Continuum fluid mechanics (CFM)

- No gap/space between fluid particles
- Fluid properties vary smoothly from point to point
- Concept of fluid particle/element/cube

[8] Slip and no-slip boundary conditions: The relative velocity between a moving fluid and a solid boundary is non-zero for inviscid flow or zero for viscous flow.

(AN EXP'TAL OBSERVATION)

[9] D'Alembert's paradox: The aerodynamic drag on any non-lifting body of any shape is predicted to be zero when the inviscid, or irrotational, flow approximation is invoked.

$i.e.$, In real flow there is a nonzero drag on bodies immersed in a uniform stream.

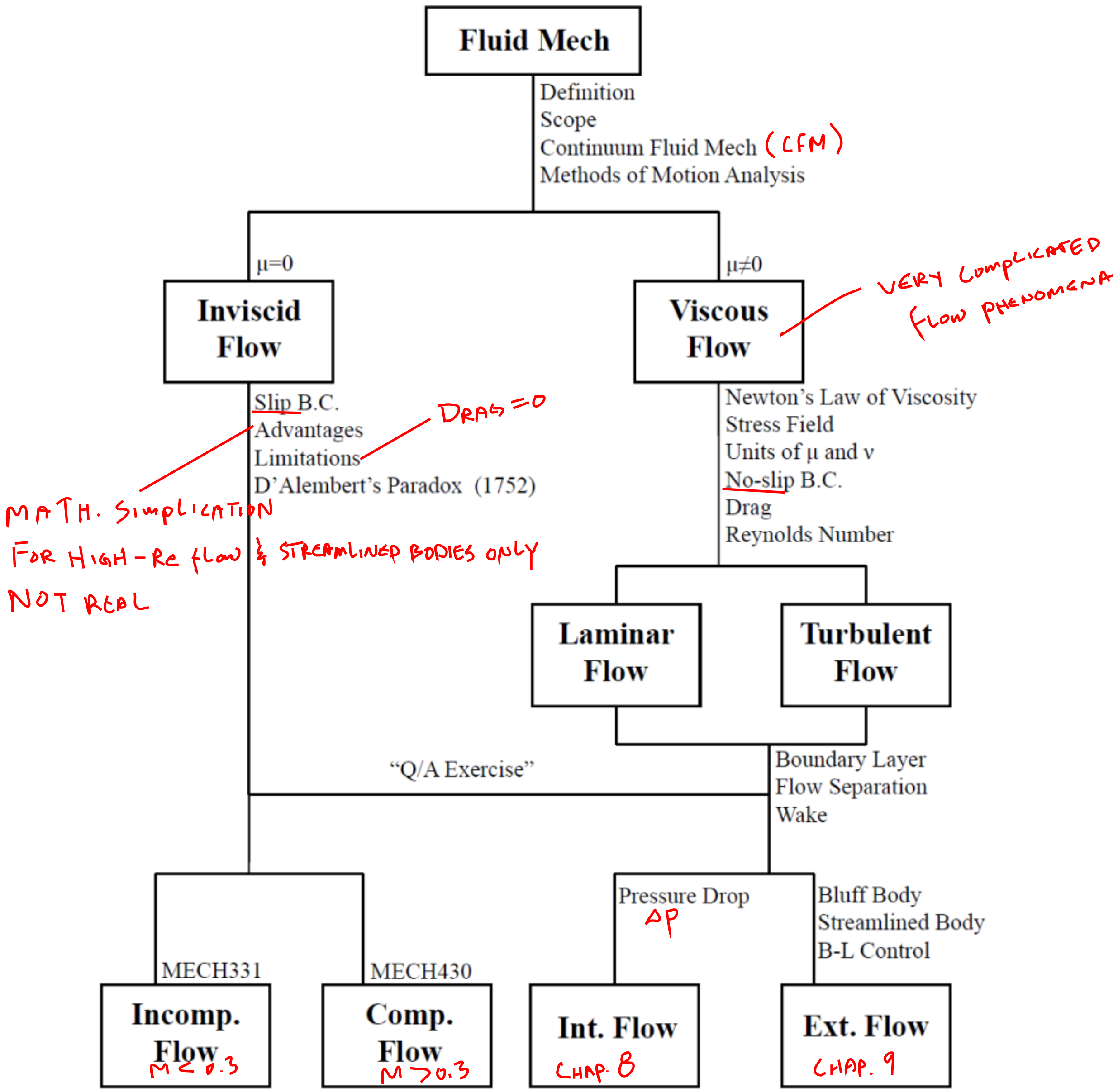
[10] The significance of μ ?

$D_f \neq 0$, $D_p \neq 0$ A SIMPLIFICATION !

VISCOUS FLOW & INVISCID FLOW

FORMATION OF BOUNDARY LAYER

Classification of fluid mechanics



SR-71 Blackbird

T_{SKIN} UP TO 1200°F ? WHY

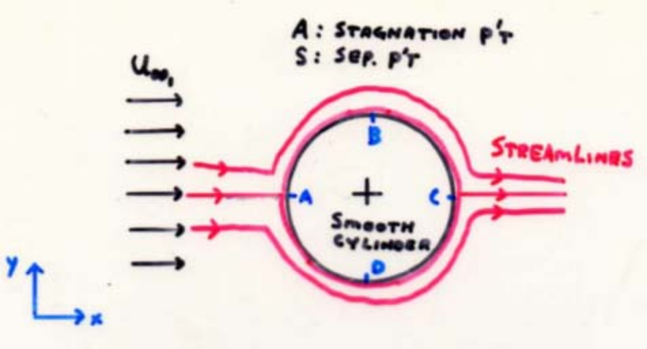
SKIN EXPANSION $\leq$ 12"

$U_c > M3.0$ @ 90,000'
AND ABOVE

Q/A: Why is the speed of a biplane limited to about 120 mph?

1 mile = 5280 ft = 1.6 km

Conceptual flow pattern over a smooth, stationary circular cylinder



Inviscid flow ($\mu = 0$)

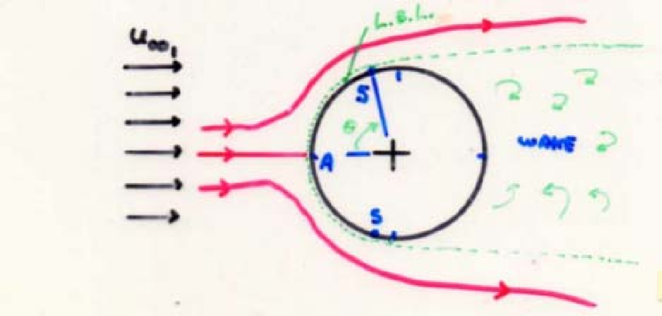
$\mu = 0$

$F_D = 0$

$F_L = 0$

$A \to B: \frac{dp}{dx} < 0$

$B \to C: \frac{dp}{dx} > 0$



Viscous flow; laminar boundary layer

$\mu \neq 0$

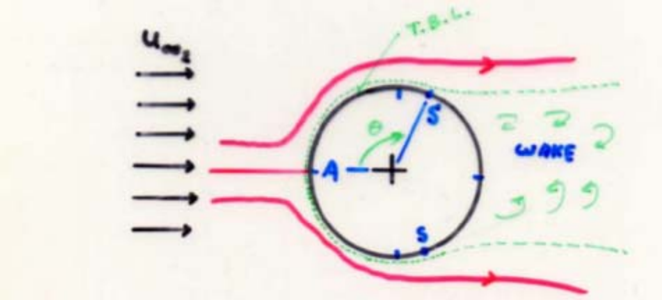
$\theta = 80°$

$R_e < 300{,}000$

$F_D \neq 0$

$F_L = 0$

LAMINAR B.L.



Viscous flow; turbulent boundary layer

$\mu \neq 0$

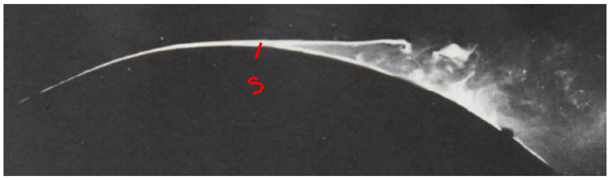
$\theta = 120°$

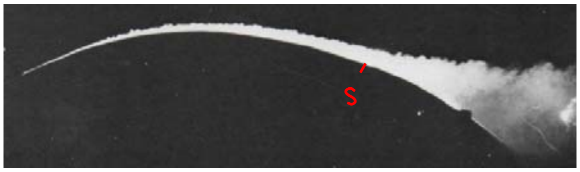
$R_e > 500{,}000$

$F_D \neq 0$

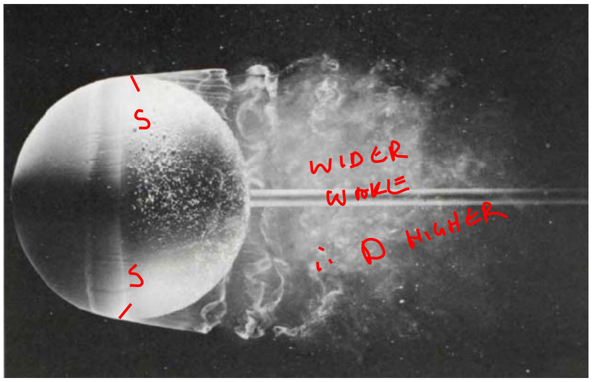
$F_L = 0$

TURBULENT B.L.

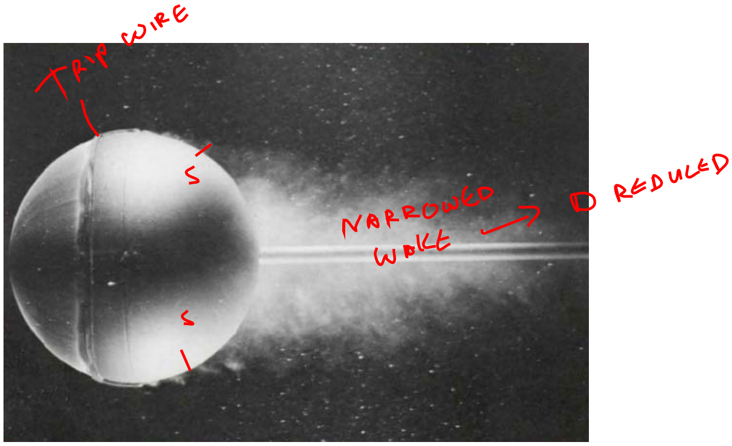




Smoke-flow pattern of a stationary sphere at $Re_D = 15{,}000$



Smooth sphere (laminar boundary layer)

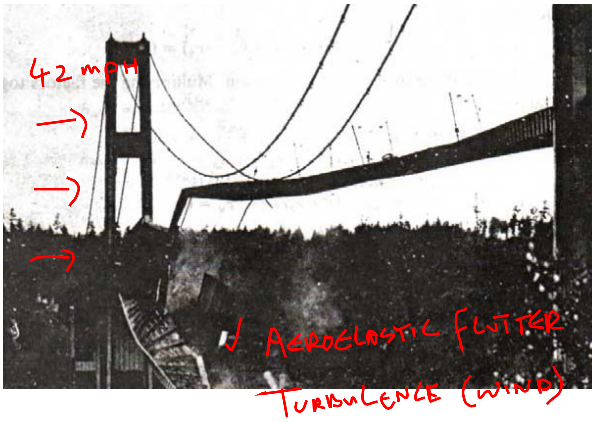


With a trip wire located at around $\theta = 70^\circ$ (turbulent boundary layer)

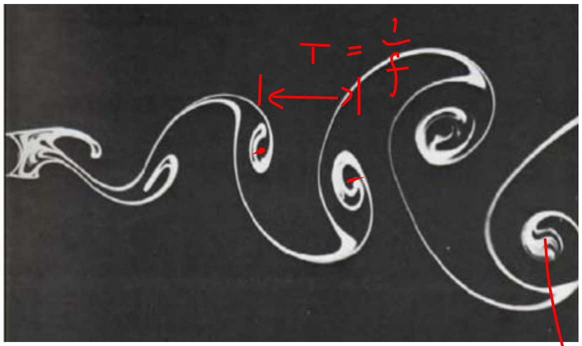
The sudden collapse of the Tacoma Narrows bridge (opened on July 1, 1940 and collapsed into Puget Sound on Nov. 7, 1940 under high wind conditions)


STRUTS
TRUSSES
CABLES

TOTAL LENGTH 5,400'
SPAN 2,800'
WIDTH 39' , HEIGHT 470'


42 mph
→
→
→

✓ AEROELASTIC FLUTTER
TURBULENCE (WIND)
VORTEX-SHEDDING WAKE


$T = \frac{1}{f}$

von Karman vortex shedding wake

"NO VORTICITY, NO SOUND."

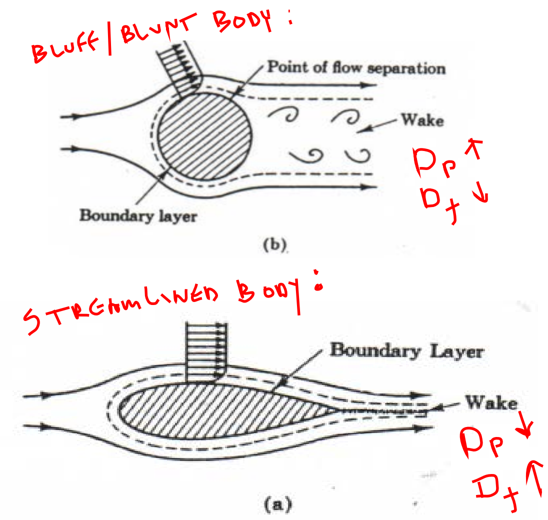
VORTICES

T = VORTEX SHEDDING PERIOD

f = VORTEX-SHEDDING FREQ.

Q/A : WHAT IS AEOLIAN TONE ?

Streamlining of a bluff or blunt body



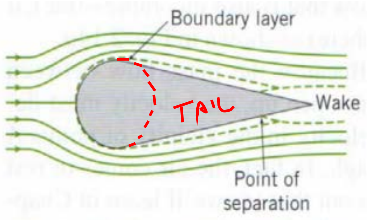


Fig. 2.16 Flow over a streamlined object.

DELAYED FLOW SEP

$D_p \downarrow$

BUT $D_f \uparrow$

Motion of fluid relative to (b) a non-streamlined object, and (a) a streamlined object

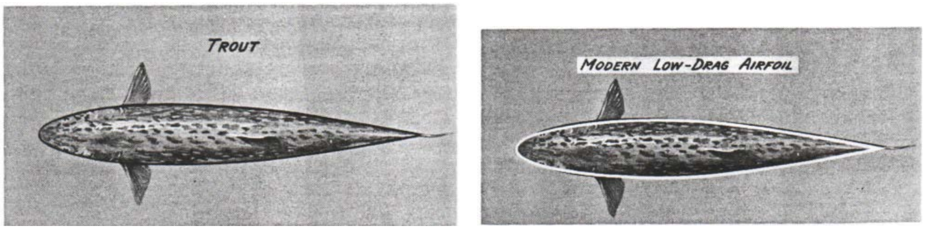
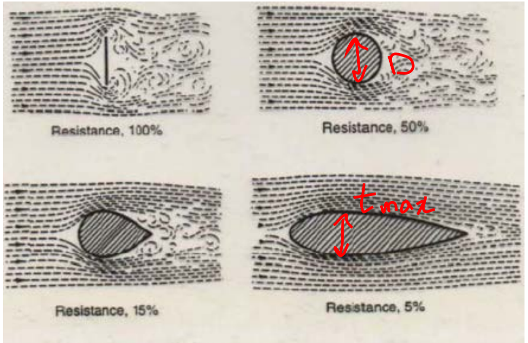


Fig. 85. Shapes of low drag can be developed not only by rational man and his intellect but also by irrational nature, through the mechanisms of gene mutation and natural selection.



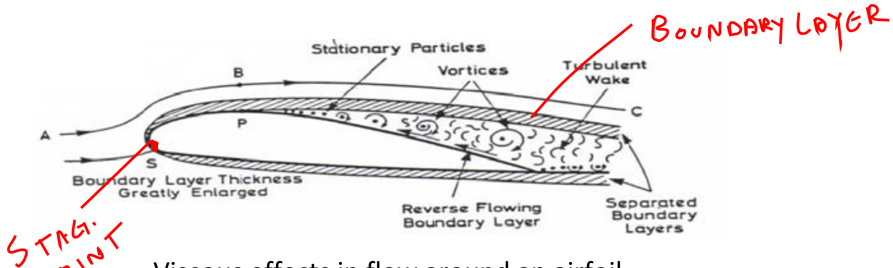
Effect of streamlining

$D = t_{max}$

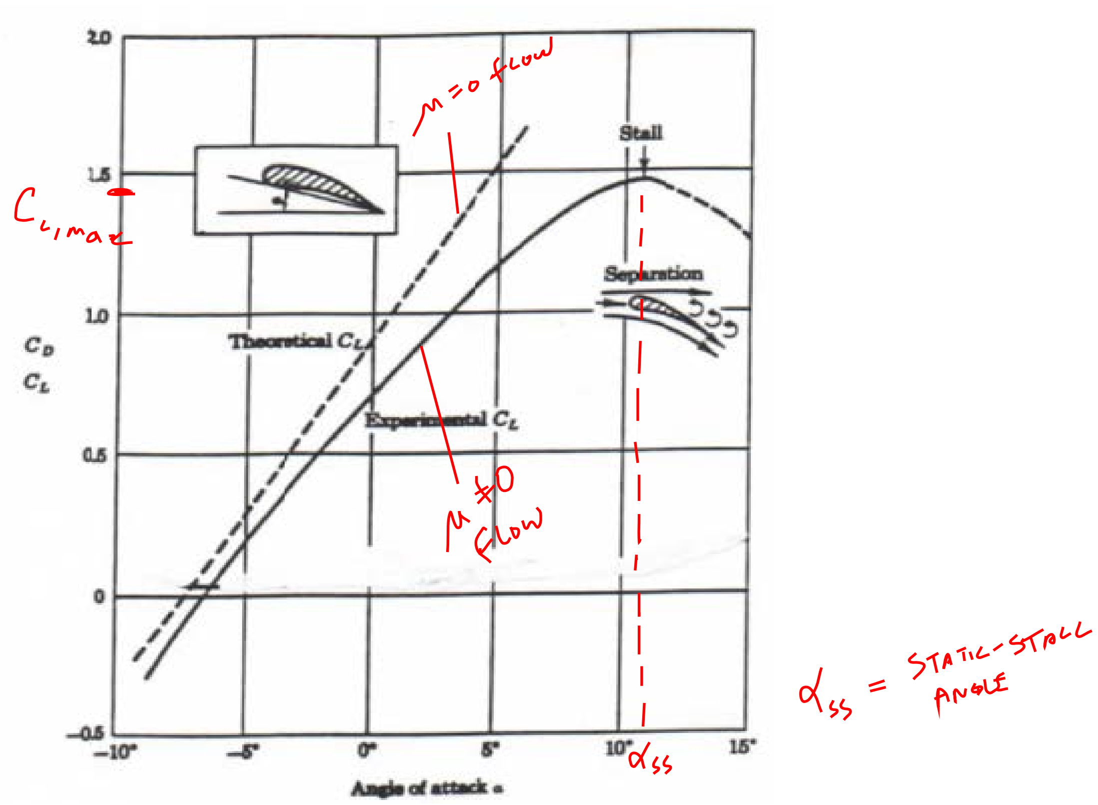
$\downarrow \qquad \downarrow$

$C_D = 1.2 \qquad C_D \cong 0.06$

C_L and C_D versus α (angle of attack or AoA) of an airfoil

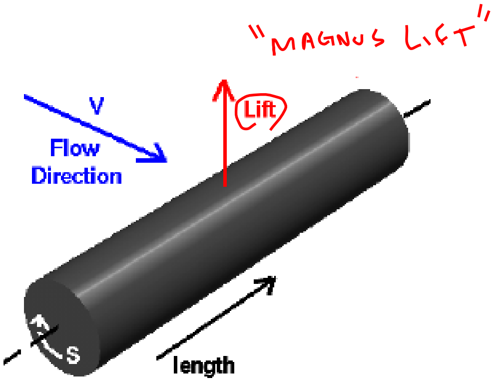


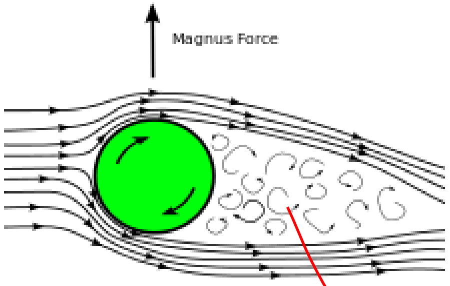
Viscous effects in flow around an airfoil



C_L and C_D versus α of an airfoil

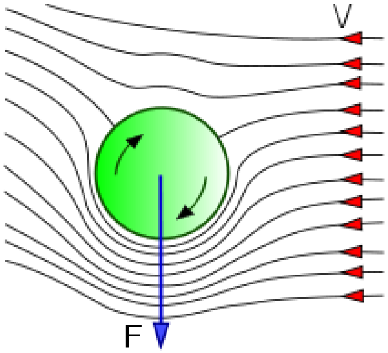
Spinning circular cylinder and Magnus Lift





μ ≠ 0 (Viscous flow)

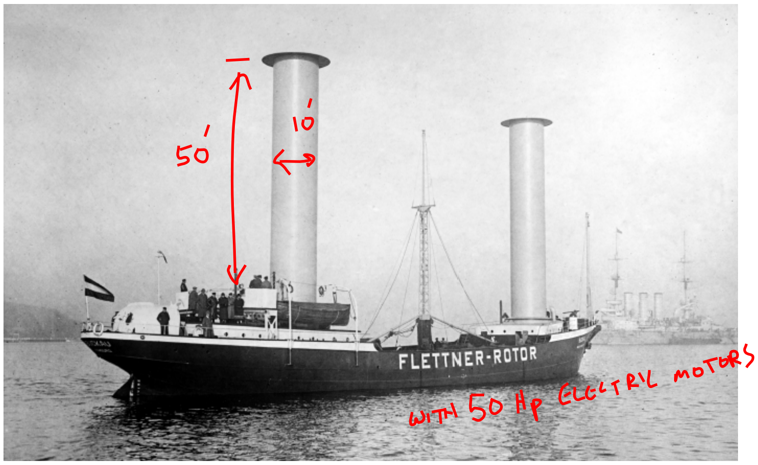
DEFLECTED WAKE (NOT SYMM.)



μ = 0 (Inviscid flow)

$$\therefore \frac{P}{\rho} + \frac{V^2}{2} = \text{CONSTANT}$$

Flettner rotor ship (1920s)

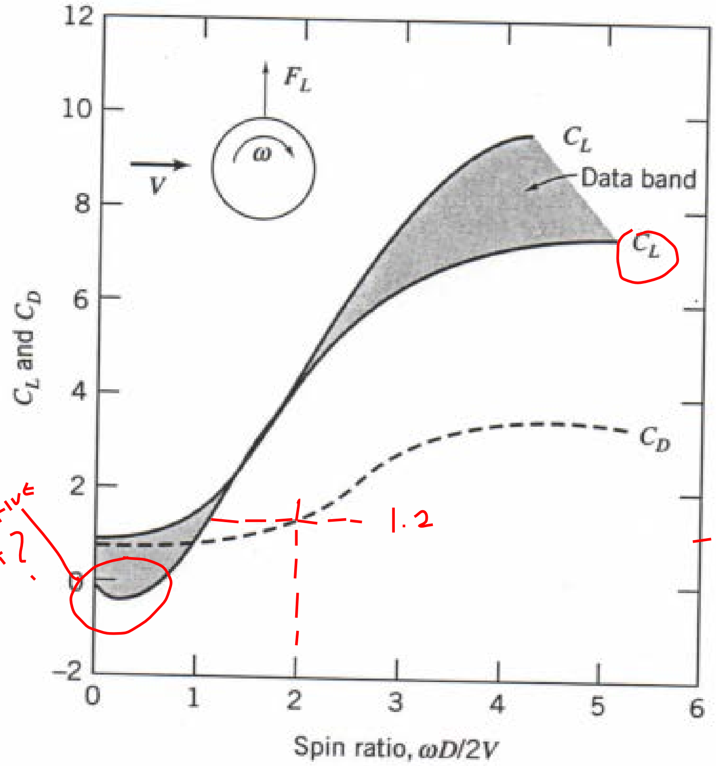


The official maiden voyage of the BUCKAU,
7 November 1924 in Kiel.

Flettner yacht on Lake Wannsee,
Berlin. Photo: Anton Flettner, 1926.

E-Ship 1, August 2008

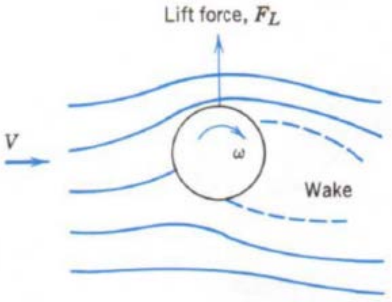
Lift and drag coefficients of a rotating circular



WHY NEGATIVE LIFT?

For $\omega = 0$,
$C_D = 1.2$
$C_L = 0$

Fig. 9.29 Lift and drag of a rotating cylinder as a function of relative rotational speed; Magnus force. (Data from [32].)



Conceptual flow pattern

where
$$C_L = \frac{F_L}{\frac{1}{2}\rho_\infty U_\infty{}^2 A_p}$$

$$C_D = \frac{F_D}{\frac{1}{2}\rho_\infty U_\infty{}^2 A_p}$$

Flettner flying car or aircraft

Anton Flettner's rotor aircraft

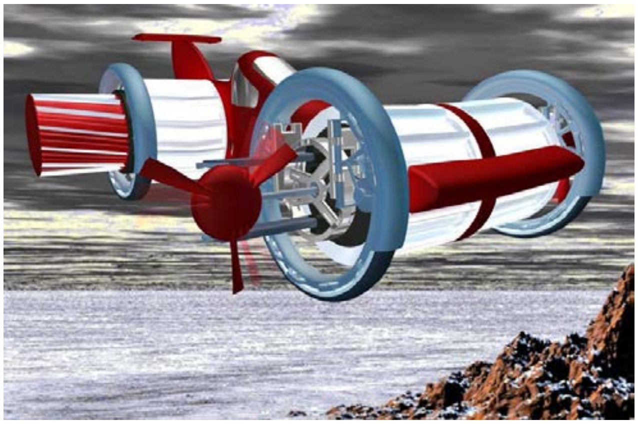
DUCTED FANS ---> THRUST

ROTATING CYLINDERS ---> LIFT

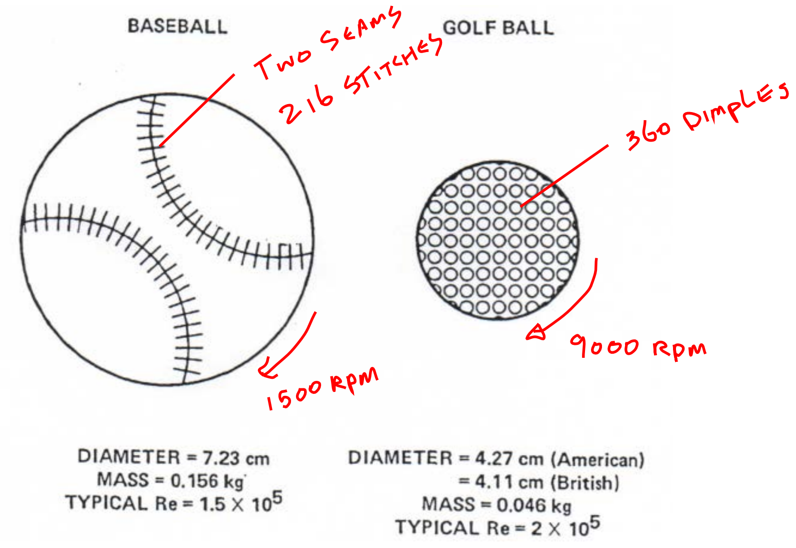
ADVANTAGES / DISADVANTAGES ?

iCar 101 Ultimate

260 km/H
1000 km RANGE



Aerodynamics of ball sports

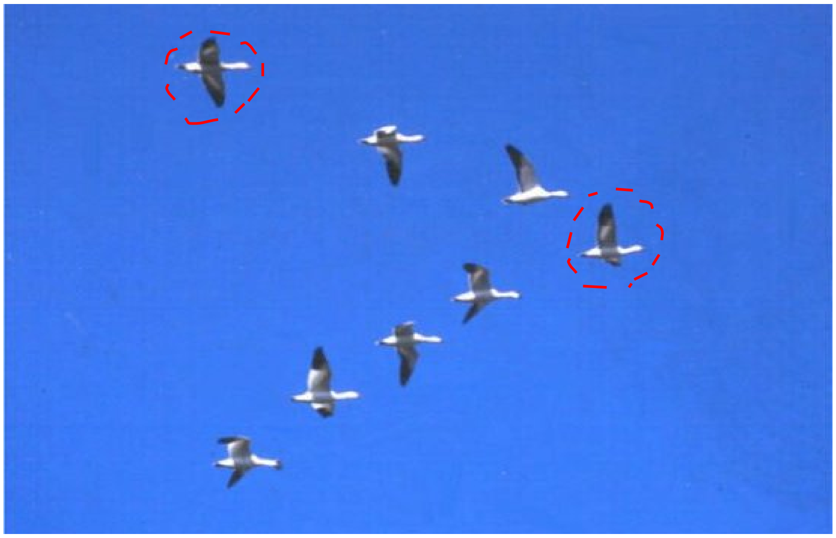


- The effects of dimples and backspin of and of a golf ball

- A curve ball

- A knuckle ball

Geese flying in V formation



LESS ENERGY

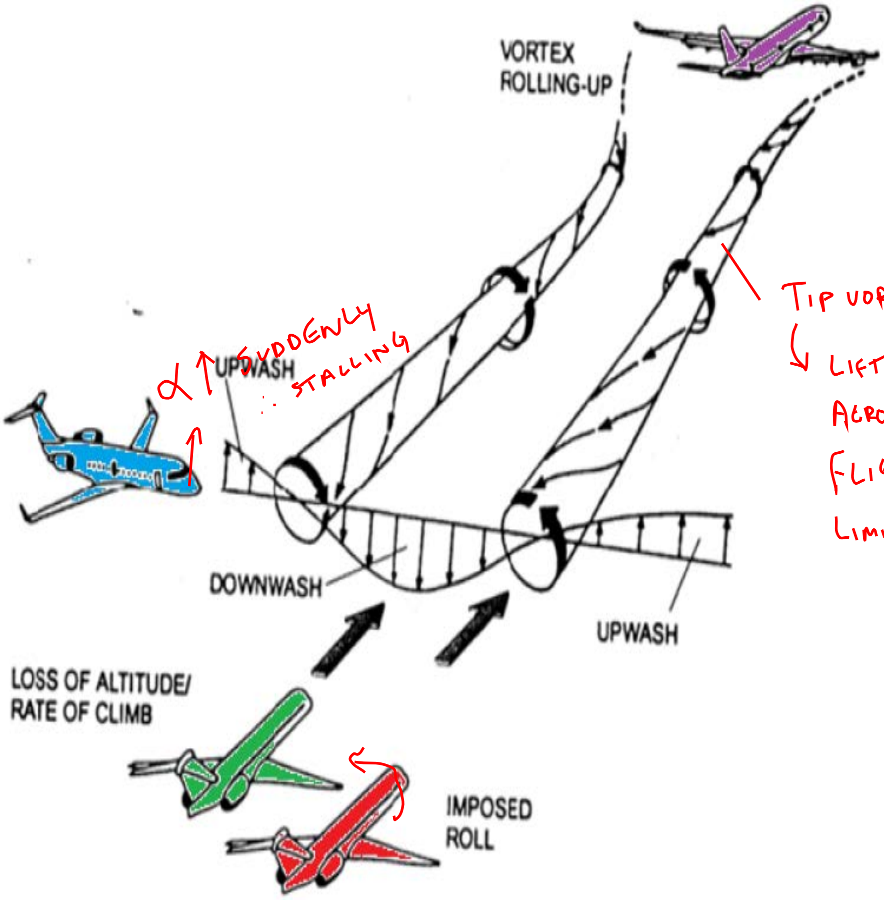
ADDITIONAL LIFT

REDUCED DRAG

FARTHER DISTANCE

WHY ? ?

Wingtip vortices and flight hazards



TIP VORTEX

↓ LIFT-INDUCED DRAG

AERODY. EFF. ↓ ($\because \frac{L}{D} \downarrow$)

FLIGHT HAZZARDS

LIMITED AIRPORT CAPACITY

Winglets

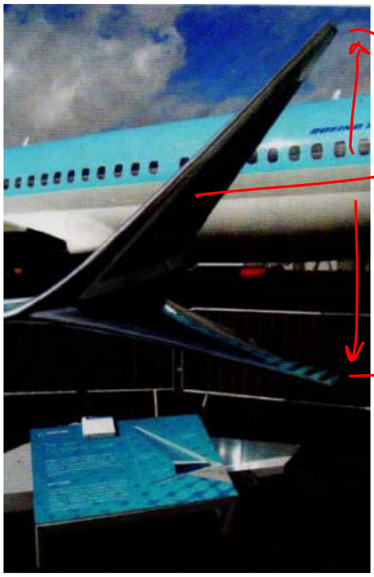
Learjet 45

A320NEO 2130 FIRM ORDERS

Wingtip devices that Airbus calls "sharklets" will be standard on the A320NEO.

SHARKLET

B737MAX ~1325 FIRM ORDERS



97"

SPLIT OR DUAL-FEATHER WINGLET