Lecture # 16: Review for Final Exam

Hui Hu
Department of Aerospace Engineering, Iowa State University
Ames, Iowa 50011, U.S.A

AERE 344 FINAL EXAM POLICY

☐ ***Don’t forget to fill out course evaluations***

☐ ***AerE344 final exam is scheduled* from 9:45am~11:45am on Tuesday, 05/07/2024.**

☐ **AERE 344 final exam policy:**

- **Open book and open class notes**
- ***You can use your calculators, computers, and tablets without WIFI functions.***

AerE344: Final Exam

- ***20 multiple-choice problems (2 points each).***
- ***Four regular problems related to pre-lab assignments and lab reports (15 points each).***
- ***Total exam time is 120 minutes, most of the students should be finish the exam within ~45 minutes.***

AerE343L: Dimensional Analysis and Similitude

Commonly used non-dimensional parameters:

$$\text{Euler number, Eu} = \frac{\Delta p}{\rho V^2} \propto \frac{\text{pressure force}}{\text{inertial force}}$$

$$\text{Reynolds number, Re} = \frac{\rho V L}{\mu} \propto \frac{\text{inertial force}}{\text{viscous force}}$$

$$\text{Froude Number, Fr} = \frac{V}{\sqrt{\text{lg}}} \propto \frac{\text{inertial force}}{\text{gravity force}}$$

$$\text{Mach Number, M} = \frac{V}{c} \propto \frac{\text{inertial force}}{\text{compressibility force}}$$

$$\text{Strohal Number, Str} = \frac{l\varpi}{V} \propto \frac{\text{centrifugal force}}{\text{inertial force}}$$

$$\text{Weber Number, We} = \frac{V^2 l \rho}{\sigma} \propto \frac{\text{inertial force}}{\text{surface tension force}}$$

…

Similitude:

- ***Geometric similarity: the model have the same shape as the prototype.***
- ***Kinematic similarity: condition where the velocity ratio is a constant between all corresponding points in the flow field.***
- ***Dynamic similarity: Forces which act on corresponding masses in the model flow and prototype flow are in the same ratio through out the entire flow***

Measurement Uncertainties

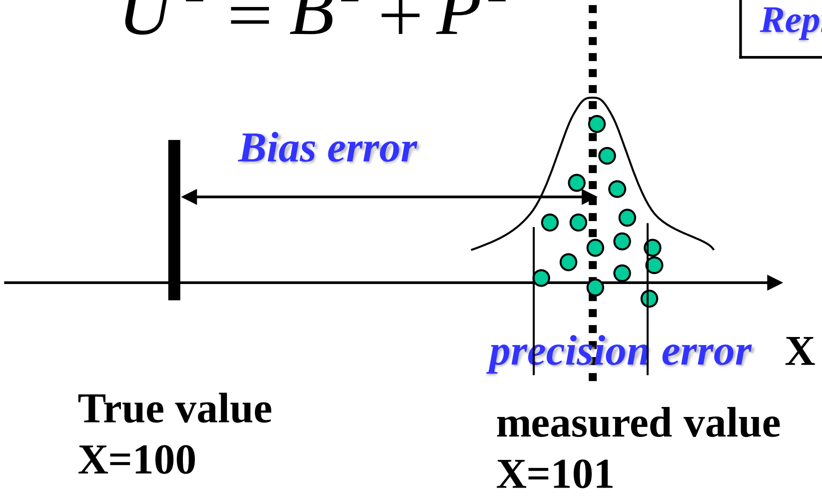
- ***"Error" is the difference between the experimentally-determined value and its true value; therefore, as error decreases, accuracy is said to increase.***

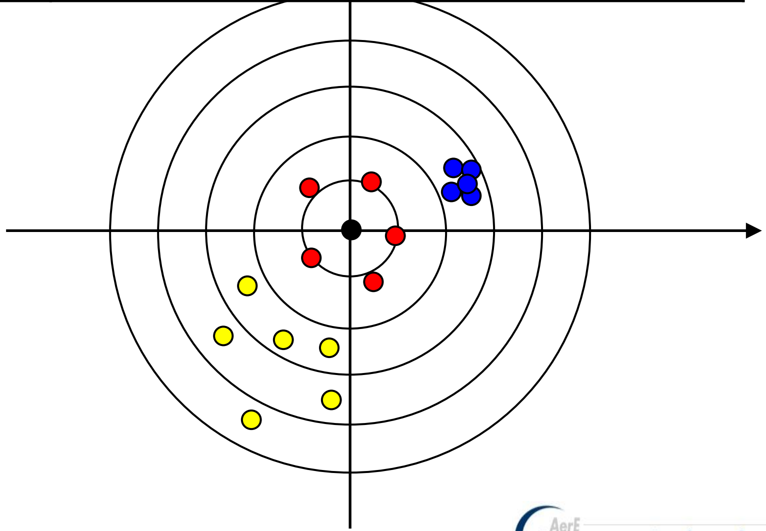
$$A_{error} = A_{measured} - A_{true} \qquad \Rightarrow \qquad E = A_m - A_{true} \qquad E_{relative} = \frac{A_{error}}{A_{true}}$$

- ***Total error, U, can be considered to be composed of two components:***
  - ***a random (precision) component,***
  - ***a systematic (bias) component,***
  - ***We usually don't know these exactly, so we estimate them with P and B, respectively.***

$$U^2 = B^2 + P^2$$

Repeatability	***Precision Error***
Reproducibility	***Both Bias and Precision Errors***





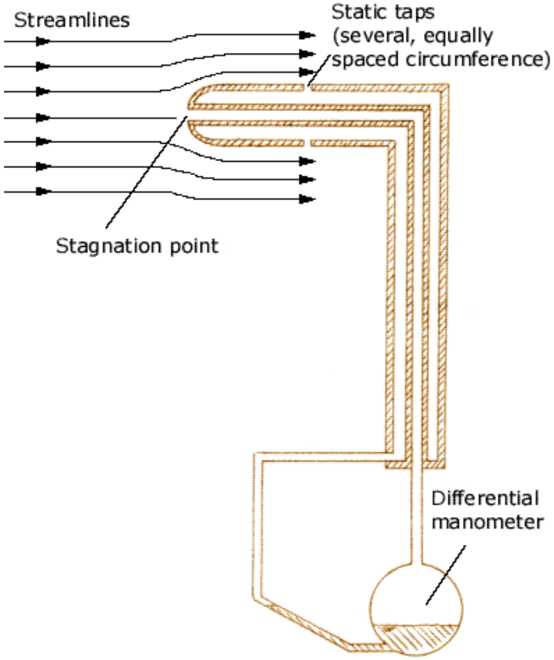
Measurement Uncertainties

Uncertainty in velocity V:

$$U_R^2 = B_R^2 + P_R^2$$

$$B_R^2 = \sum_{i=1}^{J}\left[\frac{\partial R}{\partial X_i} B_i\right]^2; \qquad P_R^2 = \sum_{i=1}^{J}\left[\frac{\partial R}{\partial X_i} P_i\right]^2$$

$$B_i = \sqrt{\sum_{j=1}^{M} B_{i_j}^2}$$



For a large number of samples (N>10)

$$P_i = 2S_i$$

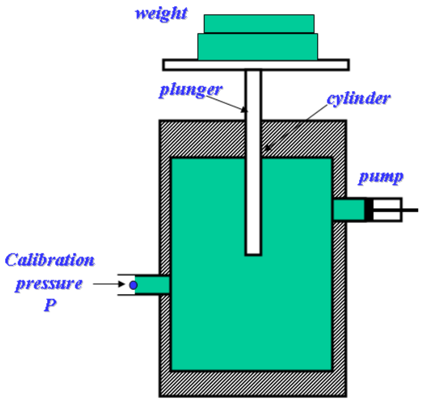
$$S_i = \left[\frac{1}{N-1}\sum_{k=1}^{N}\left[(X_i)_k - \bar{X}_i\right]^2\right]^{1/2}; \qquad \bar{X}_i = \frac{1}{N}\left[\sum_{k=1}^{N}(X_i)_k\right]$$

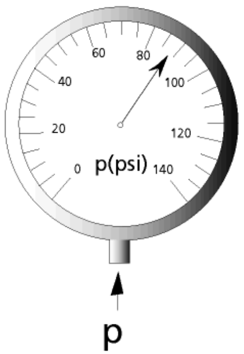
$$p_{total} = p_{static} + \frac{1}{2}\rho V^2, (Bernoulli)$$

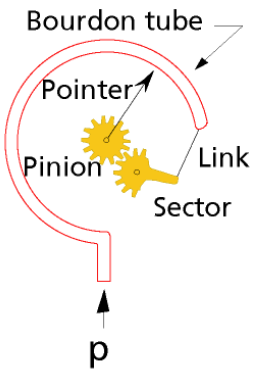
$$V = \sqrt{\frac{2(p_{total} - p_{static})}{\rho}} = \sqrt{\frac{2\Delta p}{\rho}}$$

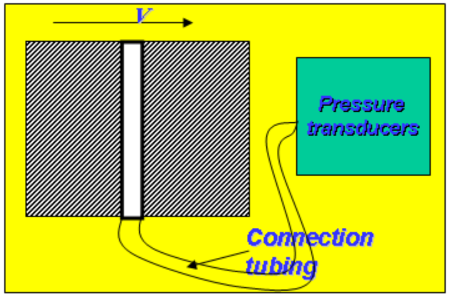
Pressure Measurement Techniques

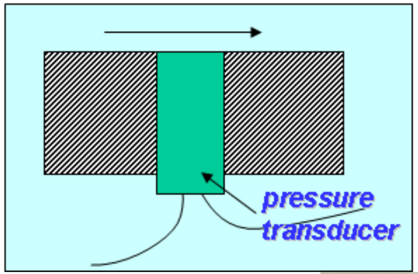
- *Deadweight gauges:*
- *Elastic-element gauges:*
- *Electrical Pressure transducers:*
- *Wall Pressure measurements*
  - *Remote connection*
  - *Cavity mounting*
  - *Flush mounting*
- *Pressure Measurements inside Flow Field:*

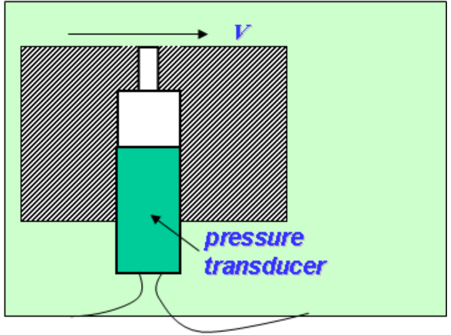












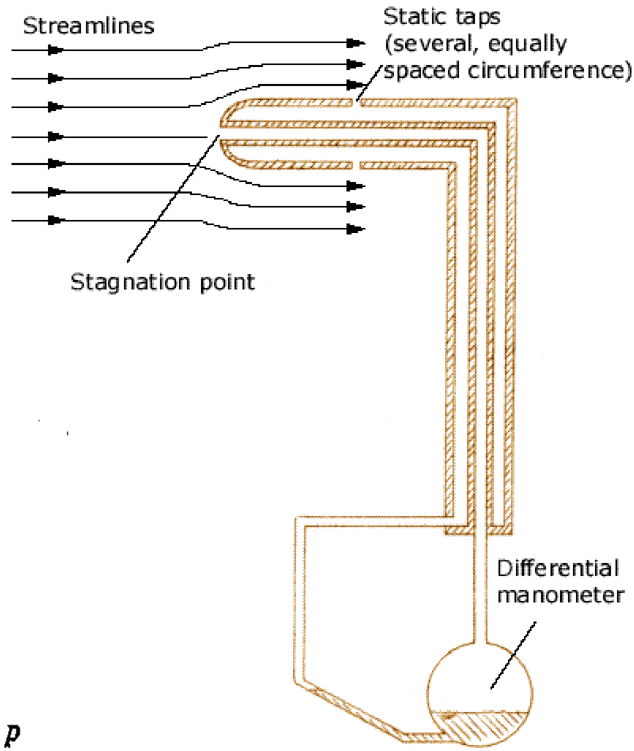
DSA3217 (Shown)

Velocity measurement techniques – Pitot –Static Probe

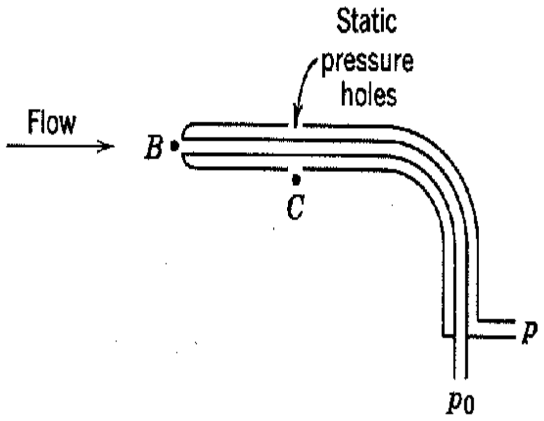
- *Advantage:*
  - *Simple*
  - *cheap*

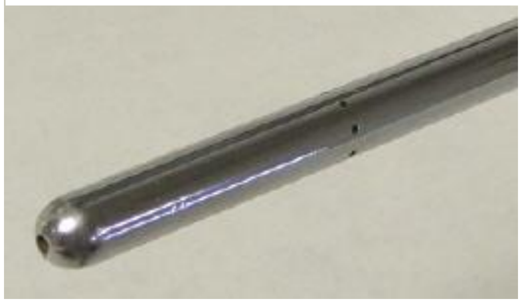
$$p_0 = p_{stat} + \frac{1}{2}\rho V^2, (Bernoulli)$$

$$V = \sqrt{\frac{2(p_0 - p_{stat})}{\rho}}$$



- *Disadvantage:*
  - *averaged velocity only*
  - *Single point measurements*
  - *Low measurement accuracy*

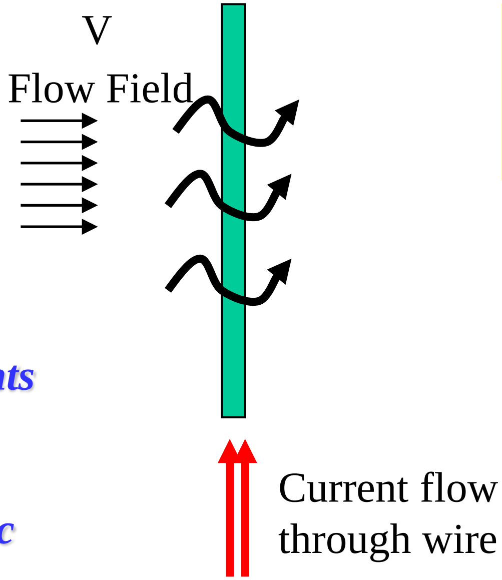




Velocity measurement techniques – Hotwire Probe

- ***Advantage:***
  - ***High accuracy***
  - ***High dynamic response***

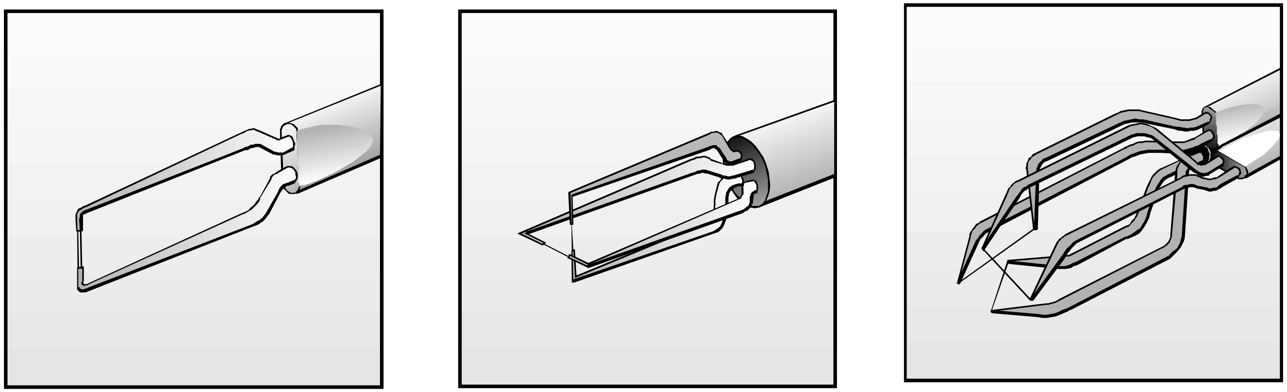
- ***Disadvantage:***
  - ***Single point measurements***
  - ***Fragile, easy to broke***
  - ***Much more expansive compared with pitot-static probe.***



The rate of which heat is removed from the sensor is directly related to the velocity of the fluid flowing over the sensor

$$mc\frac{dT_w}{dt} = i^2R_w - \dot{q}(V,T_w)$$

- ***Constant-current anemometry***
- ***Constant-temperature anemometry***

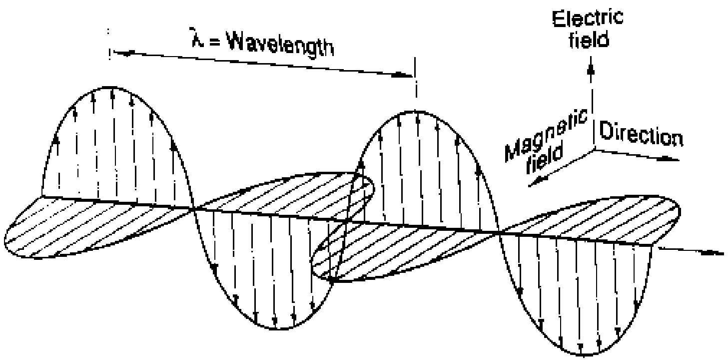


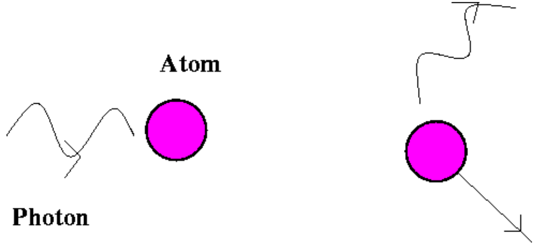
AerE311L: The nature of light

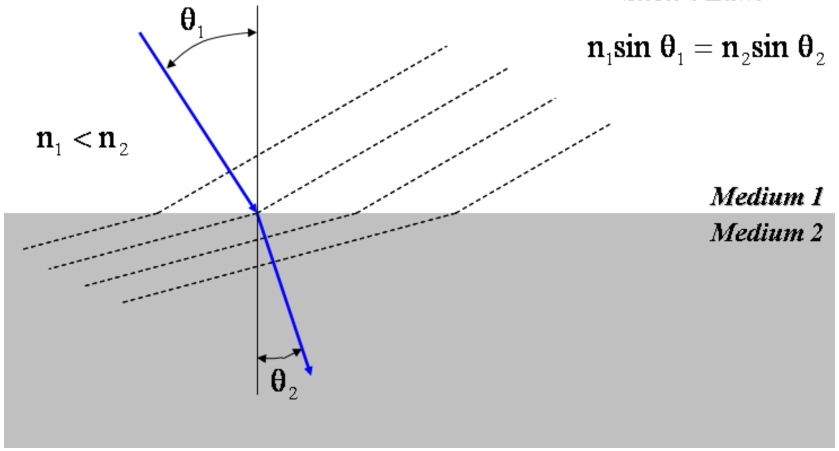
- *Light as electromagnetic waves.*
- *Light as photons.*
- *Color of light*
- *Index of reflection*

$$n = c / v = \frac{\lambda_0}{\lambda} > 1$$

$$c_0 \approx 3x10^8 \; m/s$$

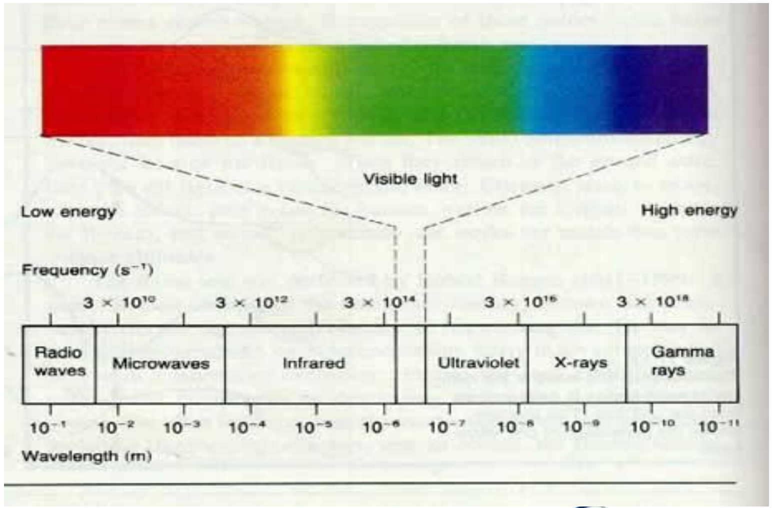






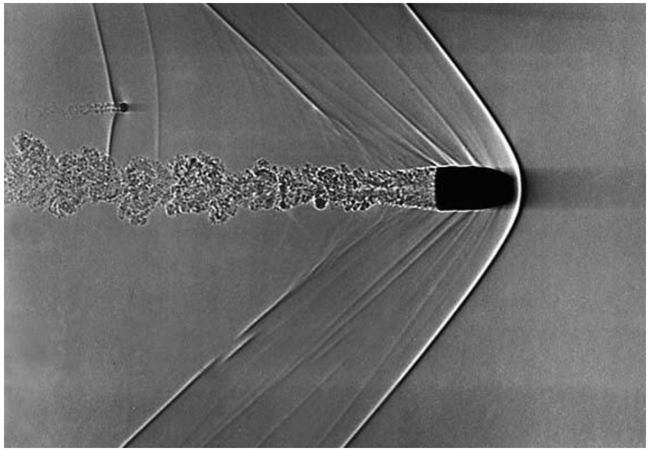
Snell's Law:

$$n_1 \sin \theta_1 = n_2 \sin \theta_2$$



Shadowgraph and Schlieren technique

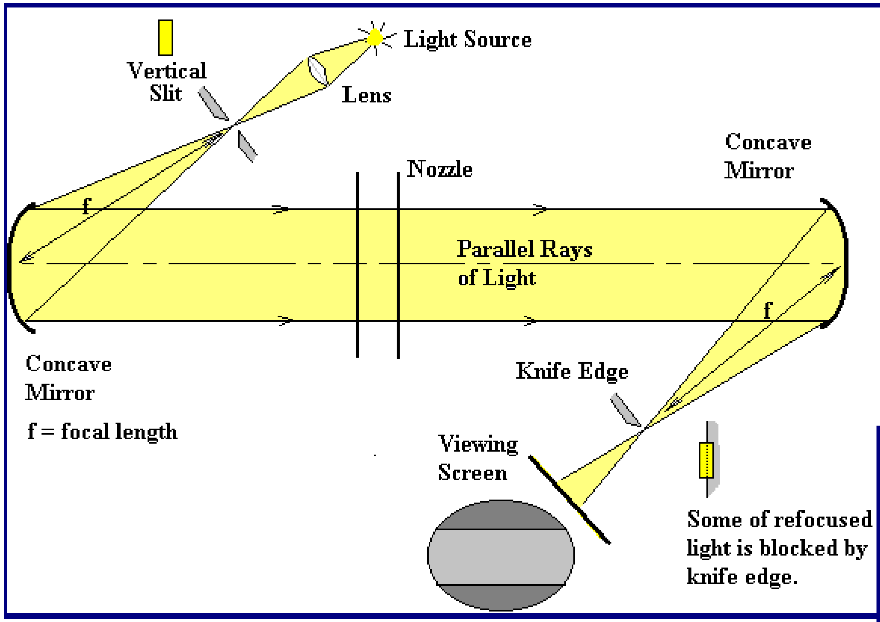
- *Index of refraction:* $n = c / v = \frac{\lambda_0}{\lambda} > 1$
- *Depend on variation of index of refraction in a transparent medium and the resulting effect on a light beam passing through the test section*
- *Shadowgraph systems: are used to indicate the variation of the second derivatives (normal to the light beam) of the index of refraction.*
- *Schlieren Systems: are used to indicate the variation of the first derivative of the index of refraction*



shadowgraph depicting the flow generated by a bullet at supersonic speeds. (by Andrew Davidhazy)

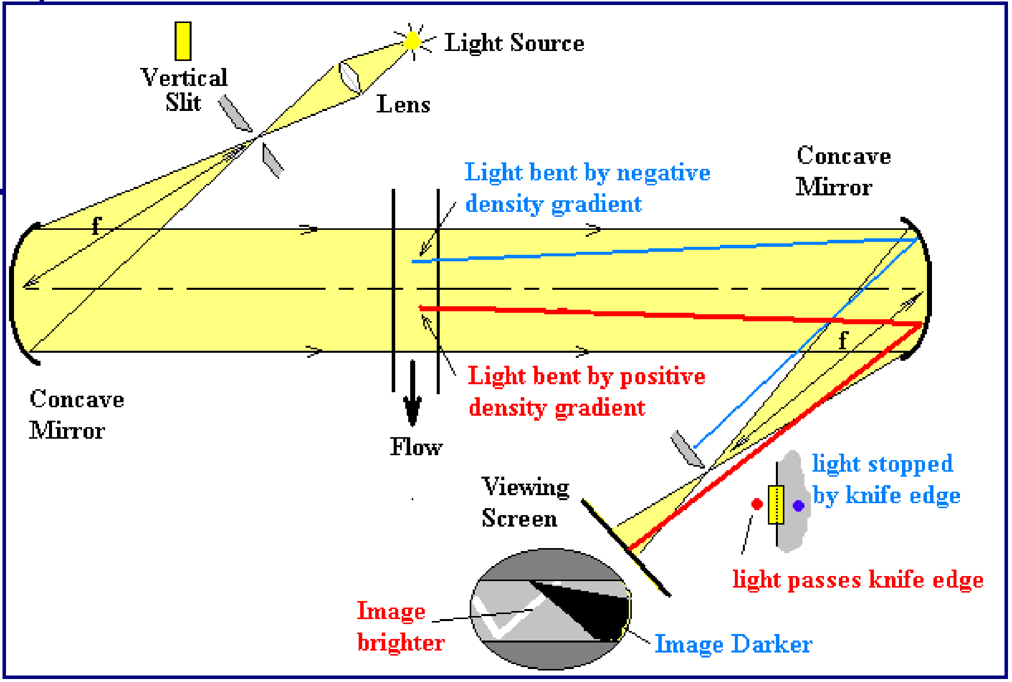
Schlieren images of the muzzle blast and supersonic bullet from firing a .30-06 caliber high-powered rifle (by Gary S. Settles)

Visualization of a Schockwaves using Schlieren technique



Before turning on the Supersonic jet

After turning on the Supersonic jet



Schlieren vs. Shadowgraph

Shadowgraph

- *Displays a mere shadow*
- *Shows light ray displacement*
- *Contrast level responds to*

$$\frac{\partial^2 n}{\partial y^2}$$

- *No knife edge used*

Schlieren

- *Displays a focused image*
- *Shows ray refraction angle, ε*
- *Contrast level responds to*

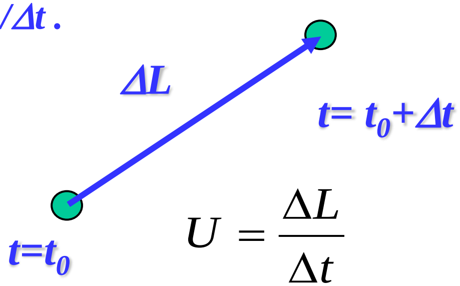
$$\frac{\partial n}{\partial y}$$

- *Knife edge used for cutoff*

Particle Image Velocimetry (PIV)

- ***Advantage:***
  - ***Whole flow field measurements***
  - ***Non-intrusive measurements***
- ***Disadvantage:***
  - ***Low temporal resolution***
  - ***Very expansive compared with hotwire anemometers and pitot-static probes.***

- *To seed fluid flows with small tracer particles (~µm), and assume the tracer particles moving with the same velocity as the low fluid flows.*
- *To measure the displacements (ΔL) of the tracer particles between known time interval (Δt). The local velocity of fluid flow is calculated by $U = \Delta L/\Delta t$.*



$$U = \frac{\Delta L}{\Delta t}$$

A. $t=t_0$

B. $t=t_0+10\ \mu s$

C. Derived Velocity field

Classic 2-D PIV measurement

PIV System Setup

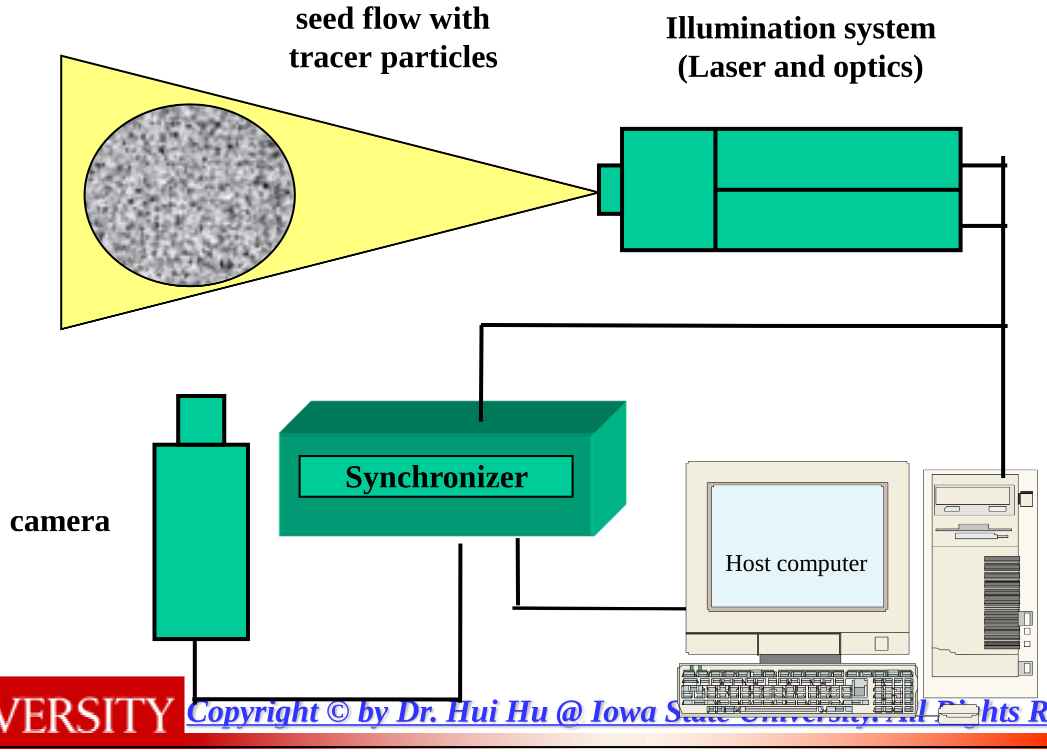
Particle tracers: *to track the fluid movement.*

Illumination system: *to illuminate the flow field in the interest region.*

Camera: *to capture the images of the particle tracers.*

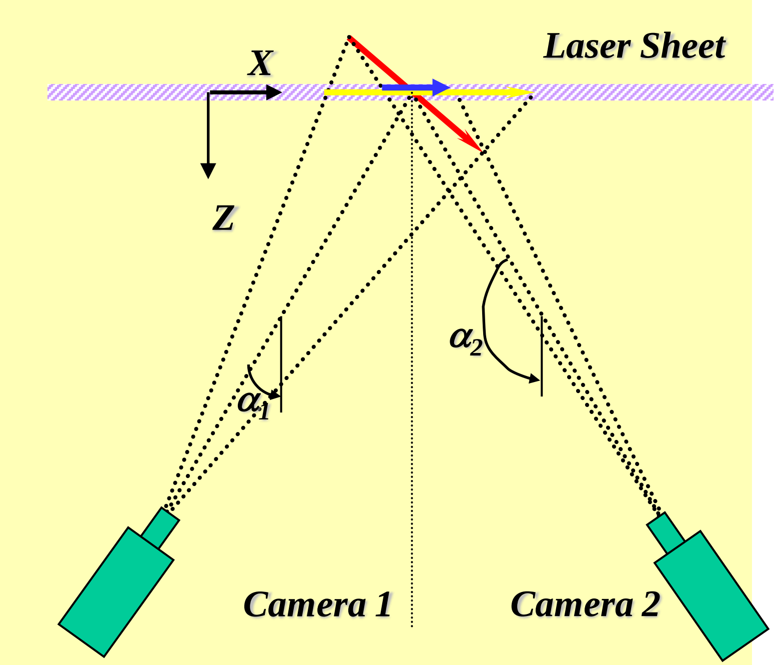
Synchronizer: *the control the timing of the laser illumination and camera acquisition.*

Host computer: *to store the particle images and conduct image processing.*

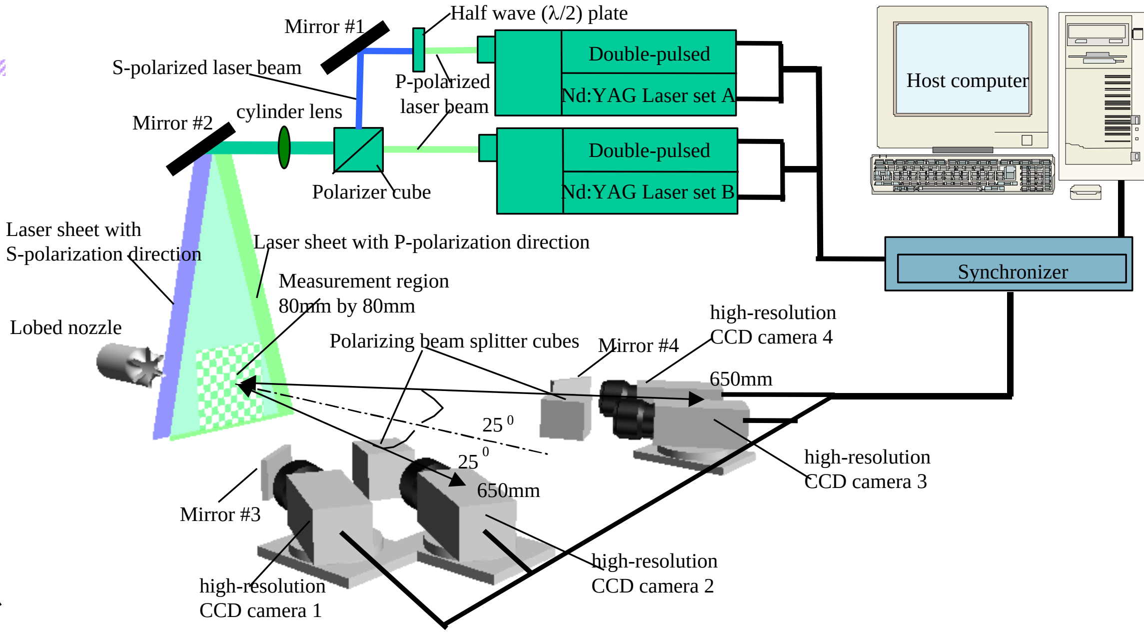


Advanced PIV techniques

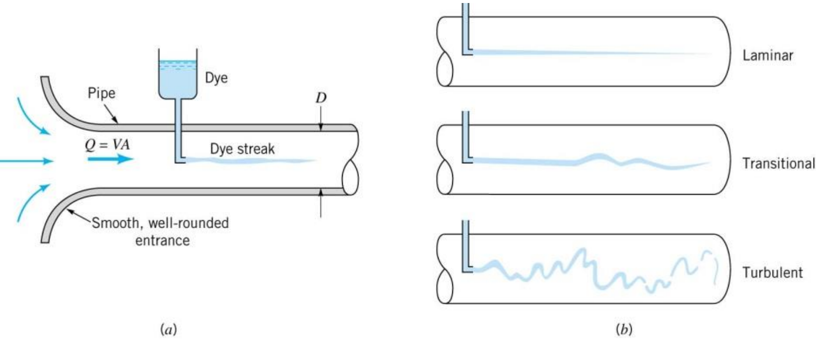
- *Stereoscopic PIV technique*
- *Dual-plane stereoscopic PIV technique*
- *3-D PTV technique*
- *Holograph PIV techniques*
- *Defocus PIV technique*

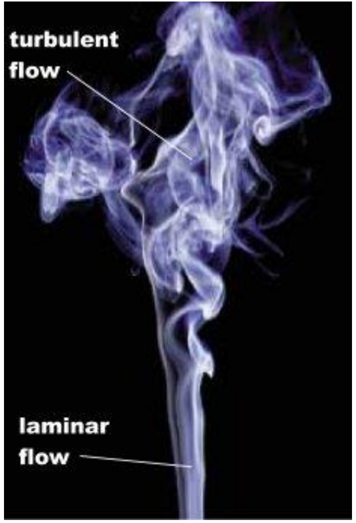


Stereo PIV technique



Laminar Flows and Turbulent Flows



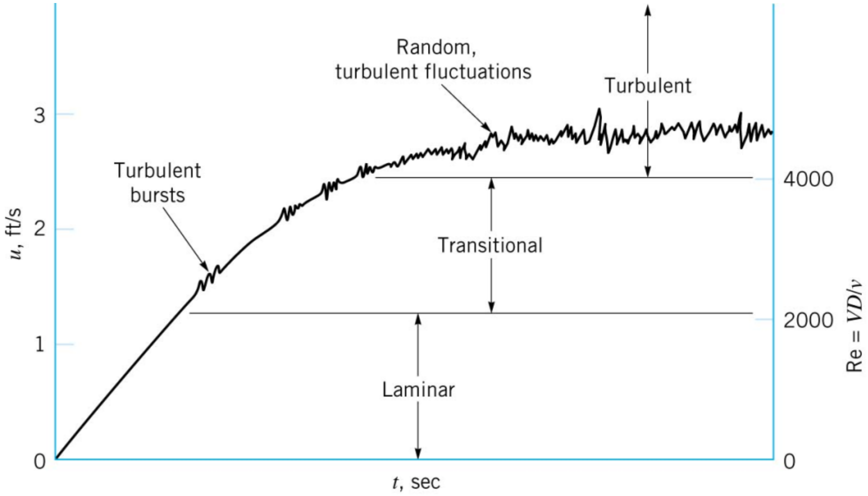


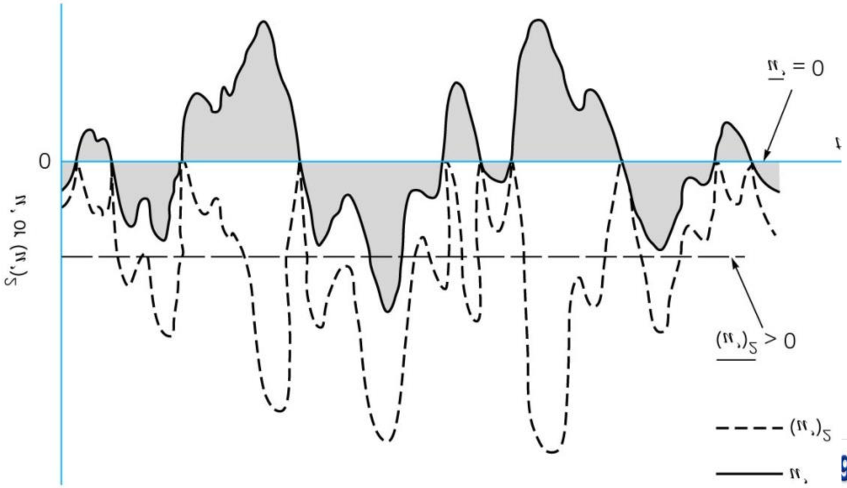
$$u=\bar{u}+u'; \quad v=\bar{v}+v' \quad w=\bar{w}+w'$$

$$\bar{u}=\frac{1}{T}\int_{t_0}^{t_0+T}u(x,y,z,t)dt \qquad \ldots$$

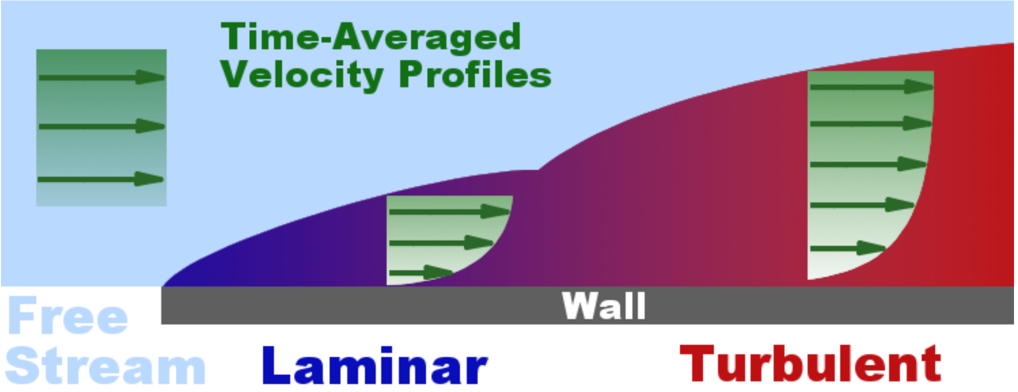
$$\overline{u'}=0; \quad \overline{v'}=0 \quad \overline{w'}=0$$

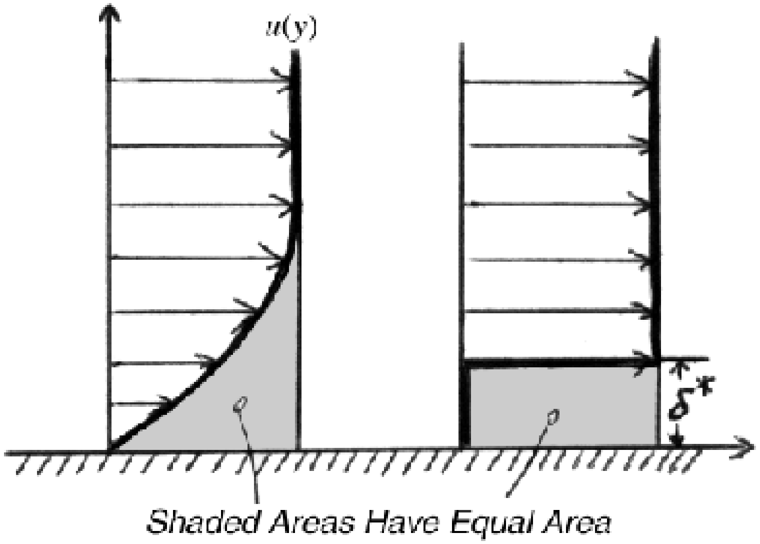
$$\overline{(u')^2}=\frac{1}{T}\int_{t_0}^{t_o+T}(u')^2dt>0; \quad \overline{(v')^2}>0 \quad \overline{(w')^2}>0$$

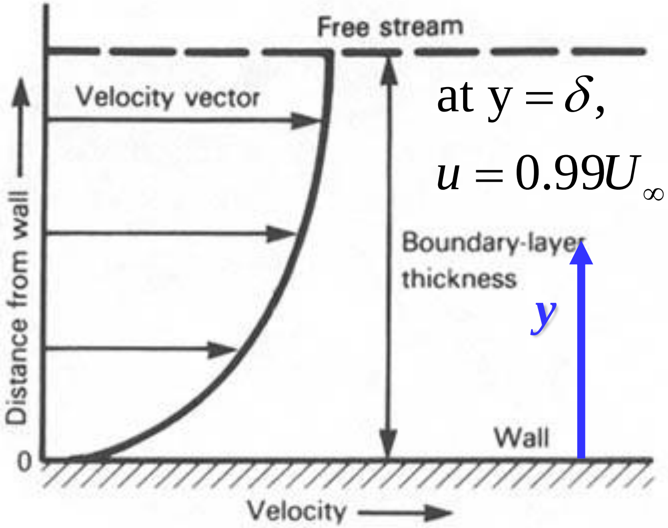




Boundary Layer Flow







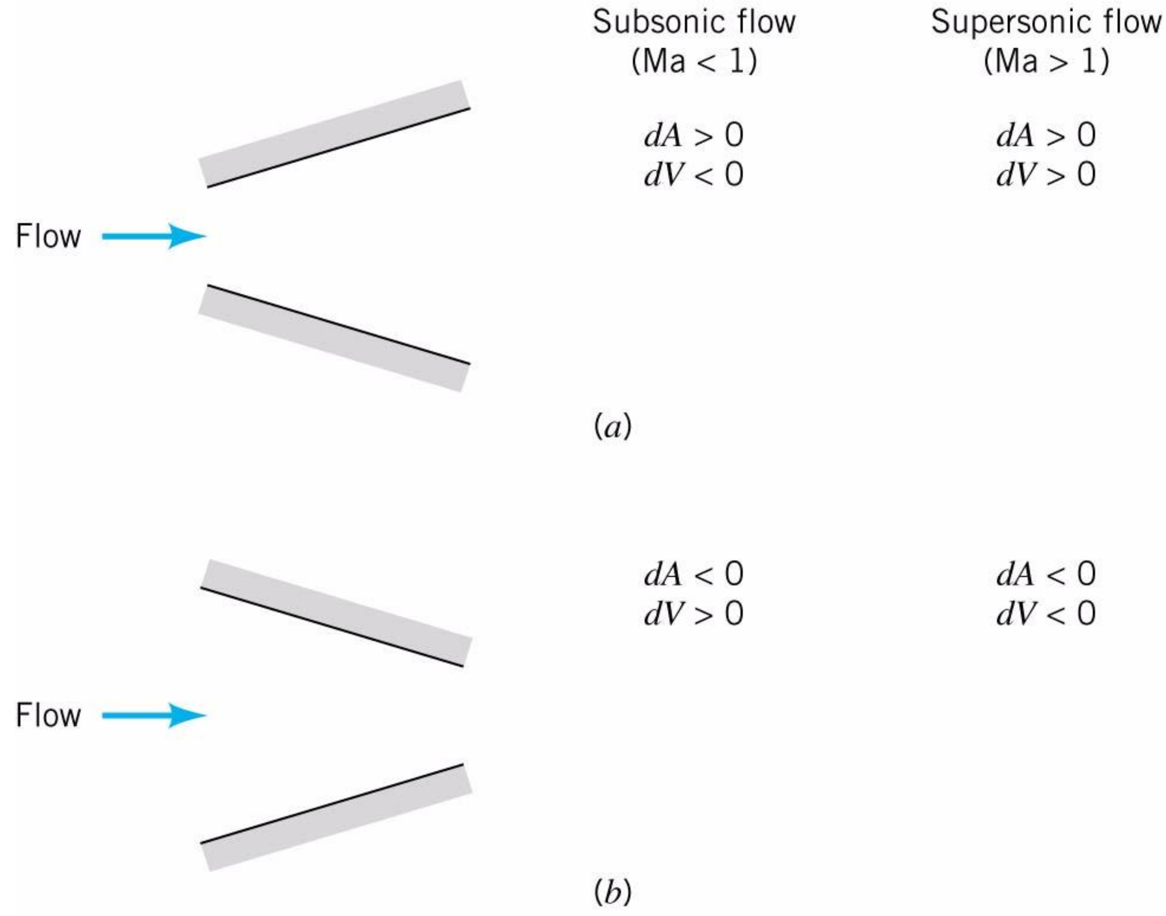
$$\text{at } y = \delta, \quad u = 0.99U_{\infty}$$

Displacement thickness: $$\delta^* \equiv \int_0^{\infty}\left(1-\frac{u}{U}\right)dy$$

Momentum thickness: $$\theta \equiv \int_0^{\infty}\frac{u}{U}\left(1-\frac{u}{U}\right)dy$$

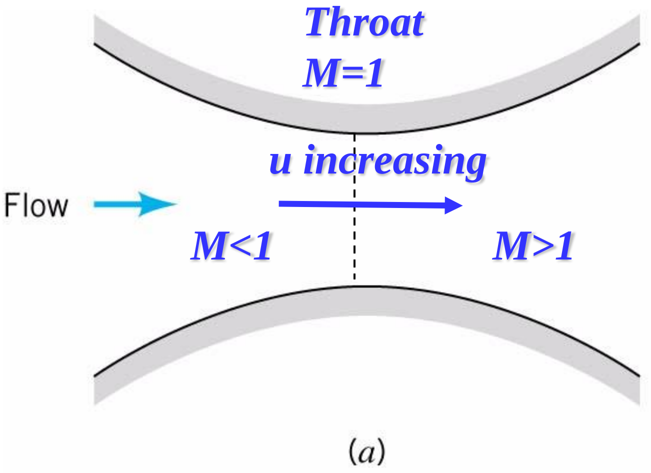
Review of Quasi-1D Nozzle Flow

$$\frac{dA}{A} = (M^2 - 1)\frac{du}{u}$$

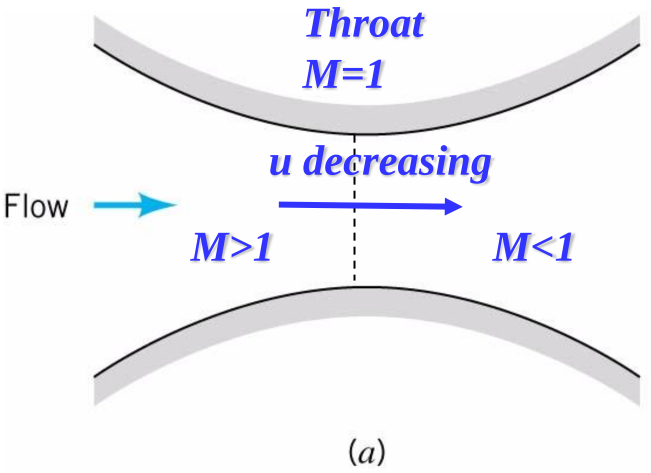


(a)

(b)



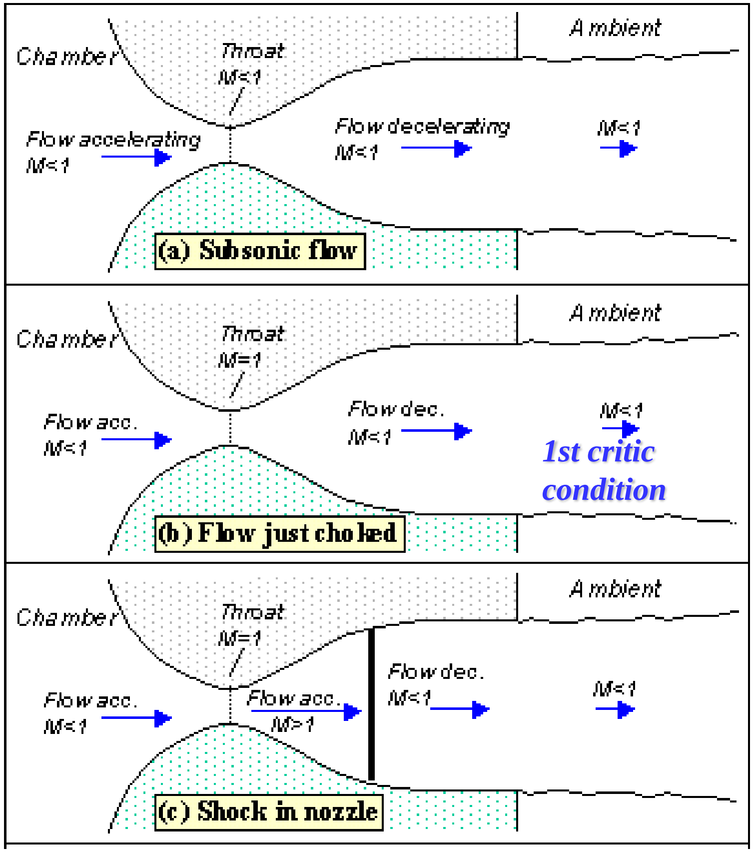
(a)



(a)

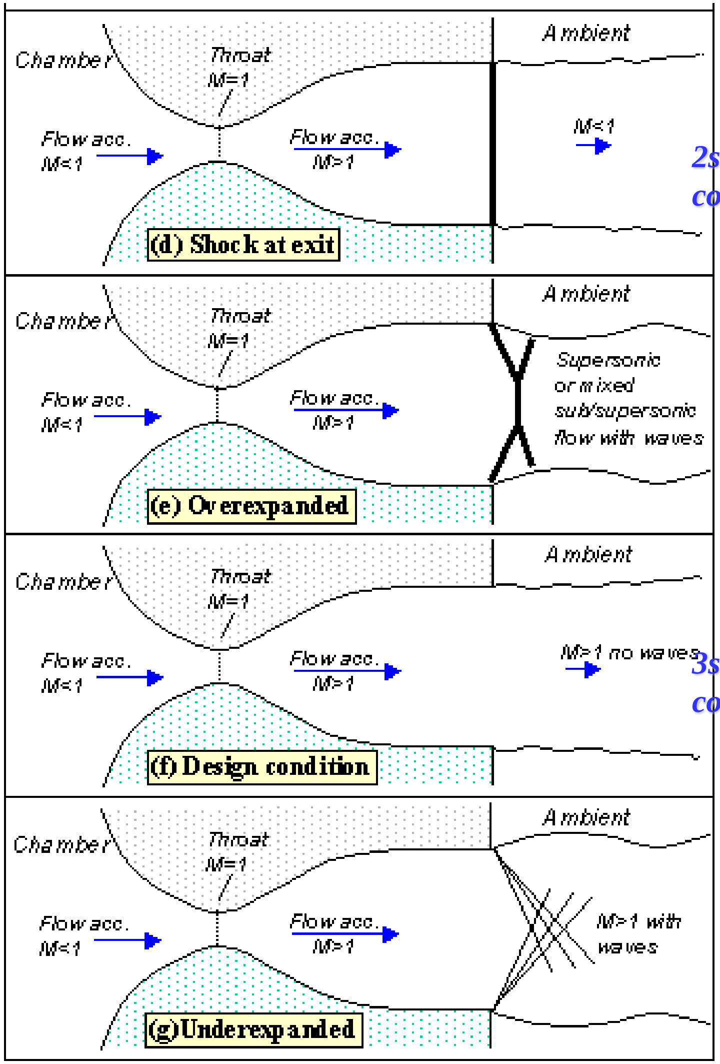
1st, 2nd and 3rd critic conditions

P_0 *increasing*



1st critic condition

P_0 *increasing*

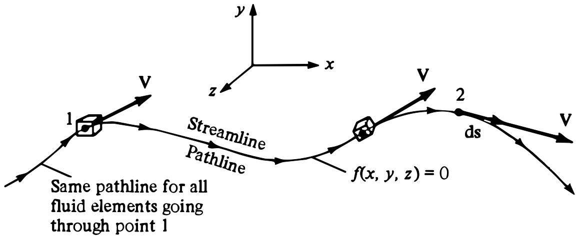


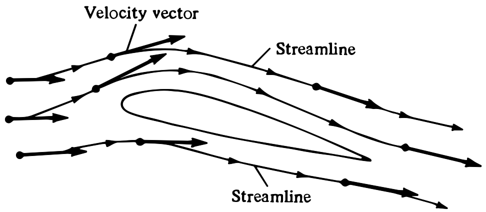
2st critic condition

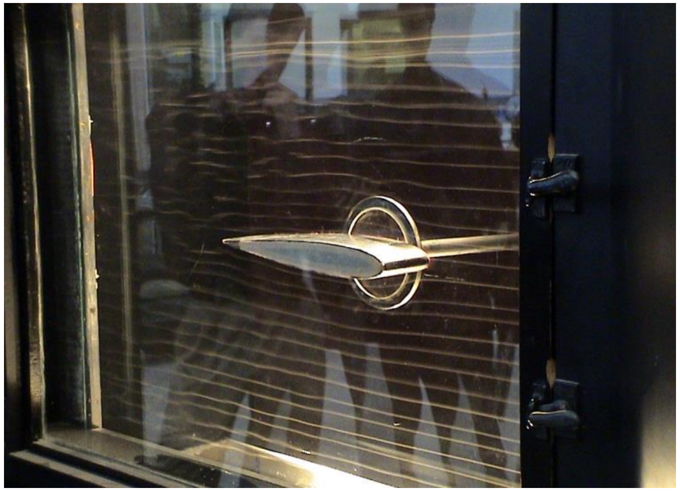
3st critic condition

Lab #1: Flow visualization by using smoke wind tunnel

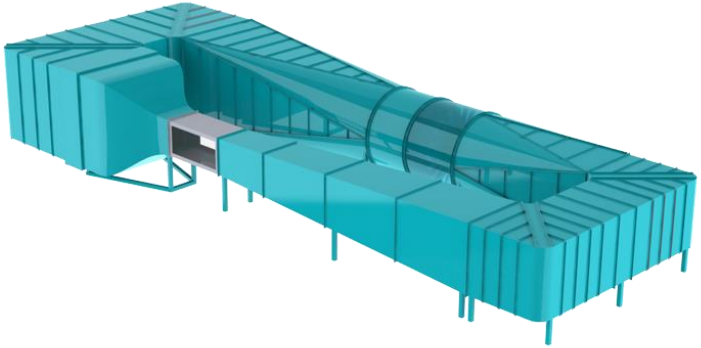
- *Path line*
- *Streak lines*
- *Streamline*

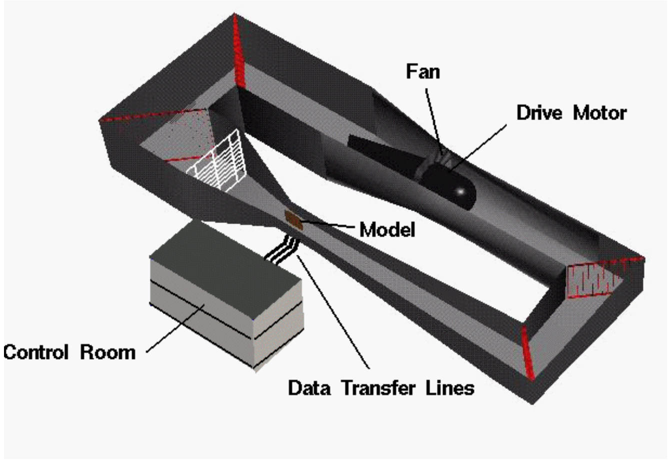


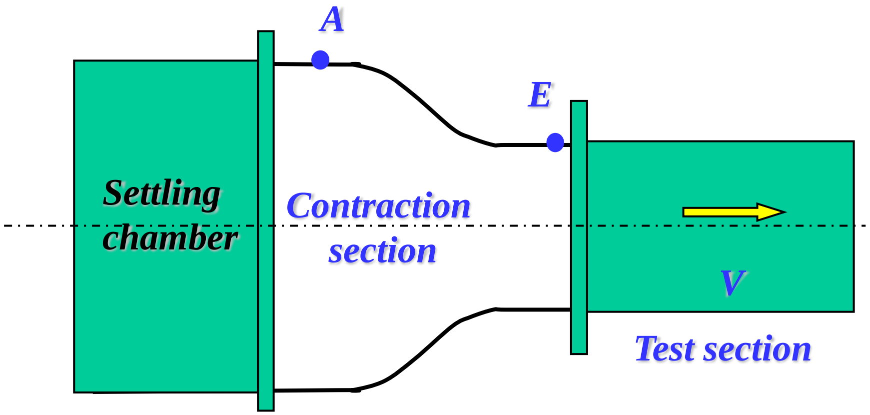




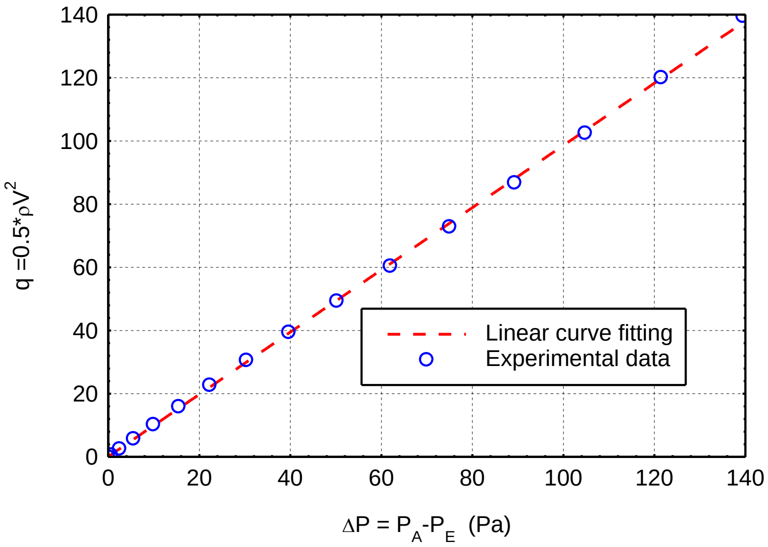
Lab#02: Wind Tunnel Calibration





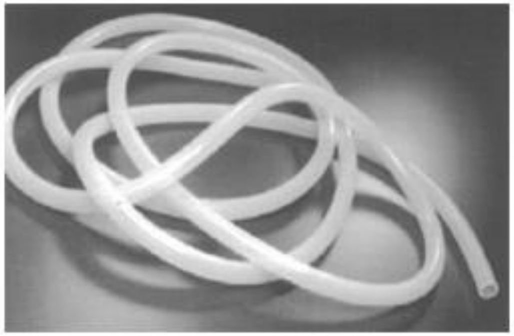


$$
\begin{aligned}
p_A - p_E &= \Delta p \\
&= C * q_T \\
&= C * \frac{1}{2}\rho V^2
\end{aligned}
$$



Lab #3: Pressure Sensor Calibration and Uncertainty Analysis

- *Task #1: Pressure Sensor Calibration experiment*
  - *A pressure sensor – Setra pressure transducer with a range of +/- 5 inH2O*
    - *It has two pressure ports: one for total pressure and one for static (or reference) pressure.*
  - *A computer data acquisition system to measure the output voltage from the manometer.*
  - *A manometer of known accuracy*
    - *Mensor Digital Pressure Gage, Model 2101, Range of +/- 10 inH2O*
  - *A plenum and a hand pump to pressurize it.*
  - *Tubing to connect pressure sensors and plenum*
- *Lab output:*
  - *Calibration curve*
  - *Repeatability of your results*
  - *Uncertainty of your measurements*

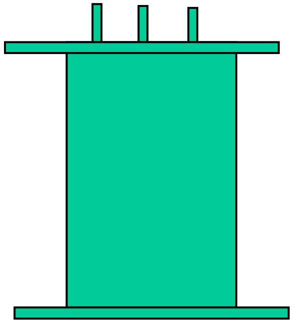


tubing

Setra pressure transducer (to be calibrated)

Mensor Digital Pressure Gage

A computer

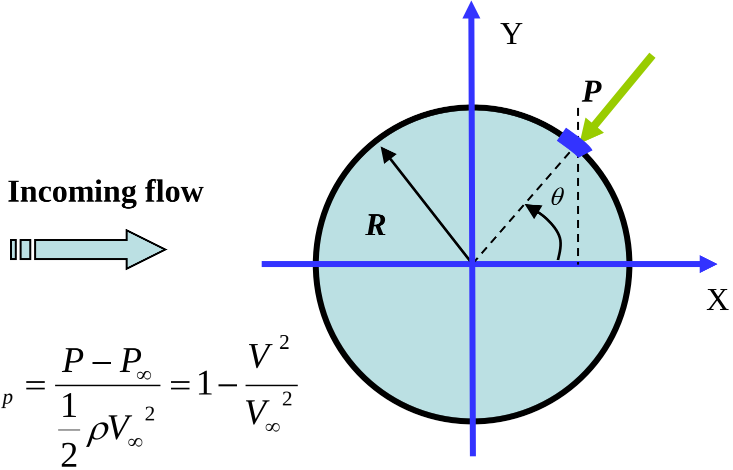


A plenum

hand pump

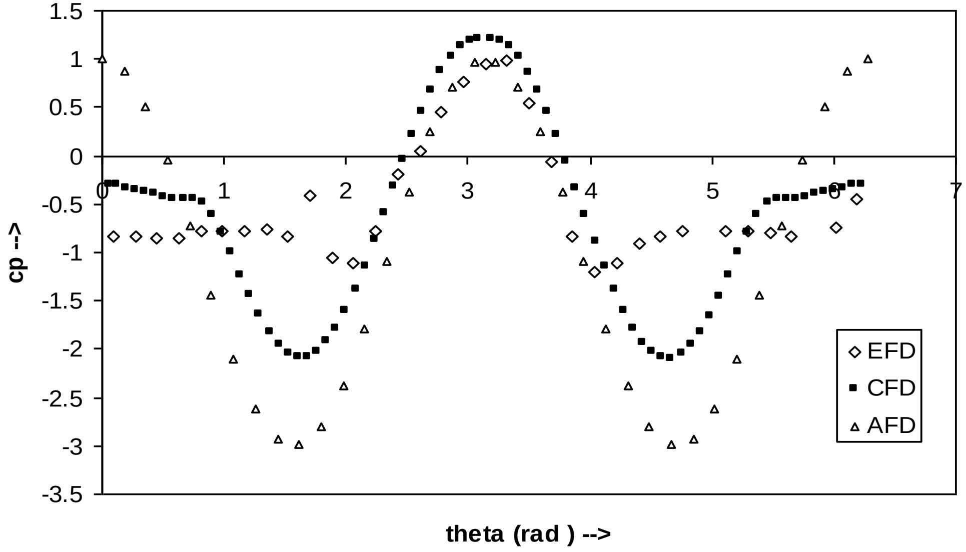
Lab#04 Measurements of Pressure Distributions around a Circular Cylinder

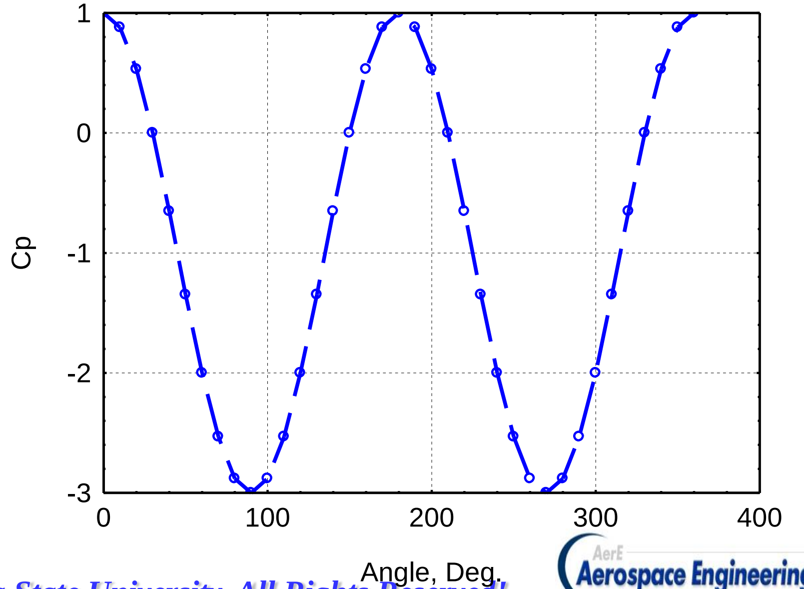
DSA3217 (Shown)



$$C_p = \frac{P - P_\infty}{\frac{1}{2}\rho V_\infty^2} = 1 - \frac{V^2}{V_\infty^2}$$

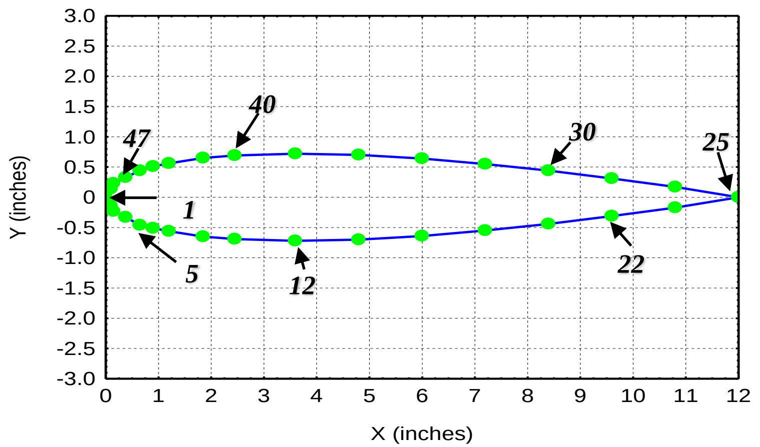
$$= 1 - \frac{(-2V_\infty \sin\theta)^2}{V_\infty^2} = 1 - 4\sin^2\theta$$

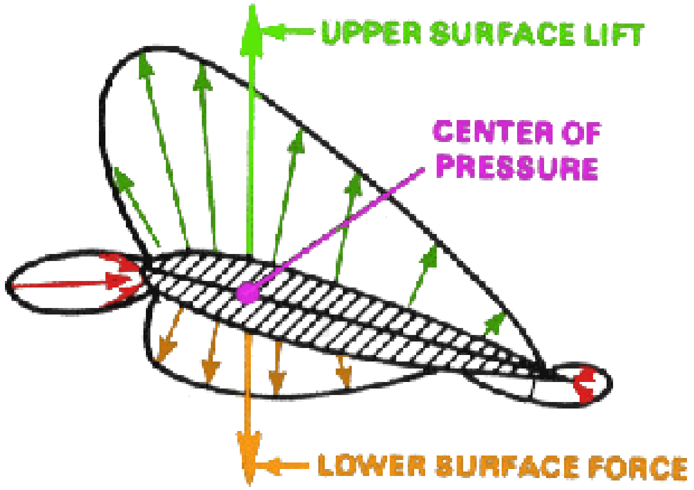




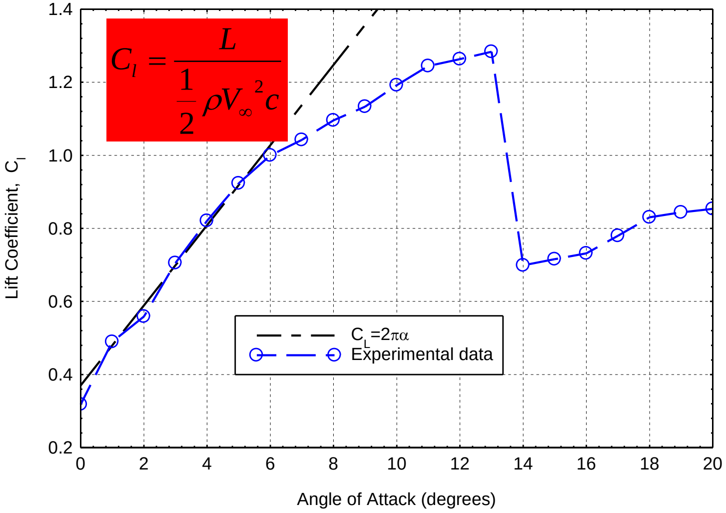
Lab#05: Airfoil Pressure Distribution Measurements

NACA0012 airfoil with 32 pressure tabs

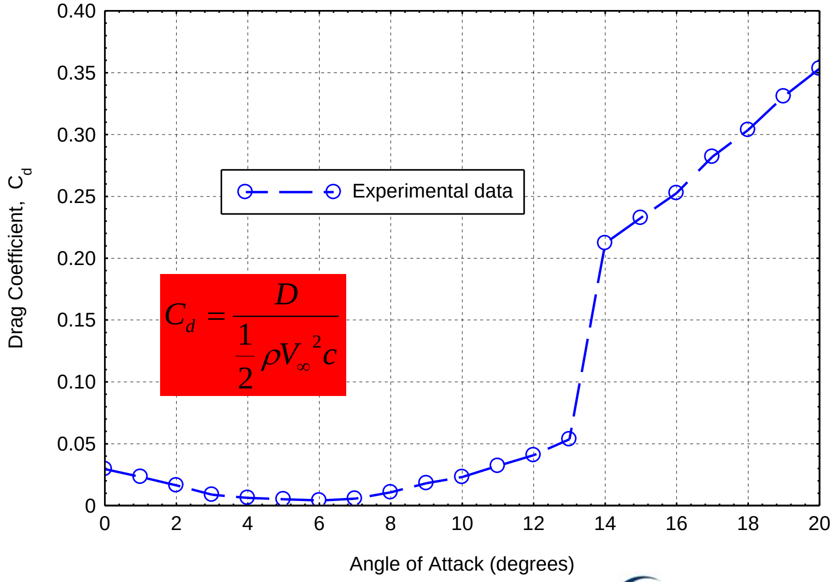




SYMMETRICAL AIRFOIL AT POSITIVE LIFT

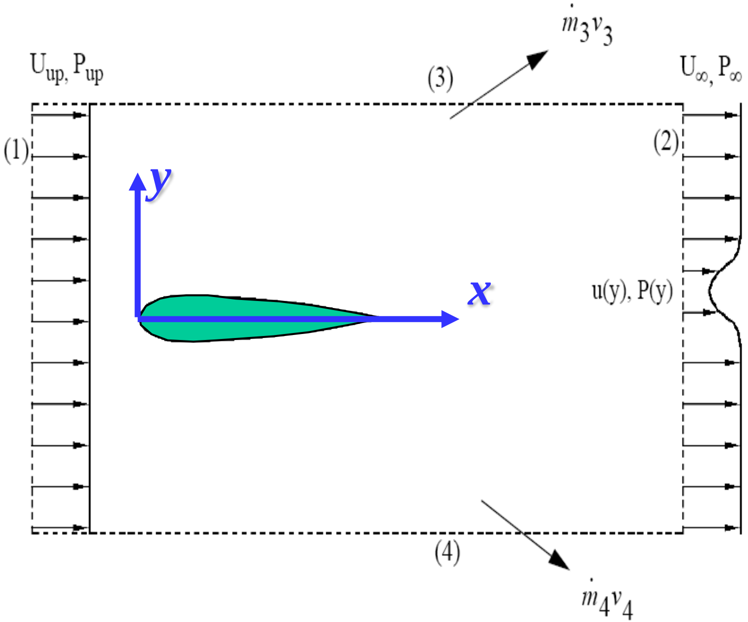


$$C_l = \frac{L}{\frac{1}{2}\rho V_\infty^2 c}$$



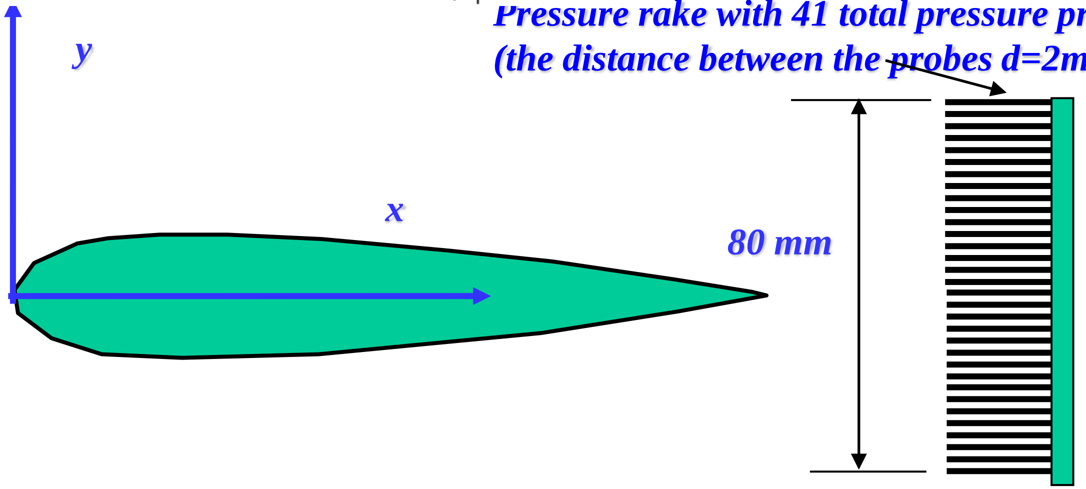
$$C_d = \frac{D}{\frac{1}{2}\rho V_\infty^2 c}$$

Lab 06: Airfoil Wake Measurements and Hotwire Anemometer Calibration



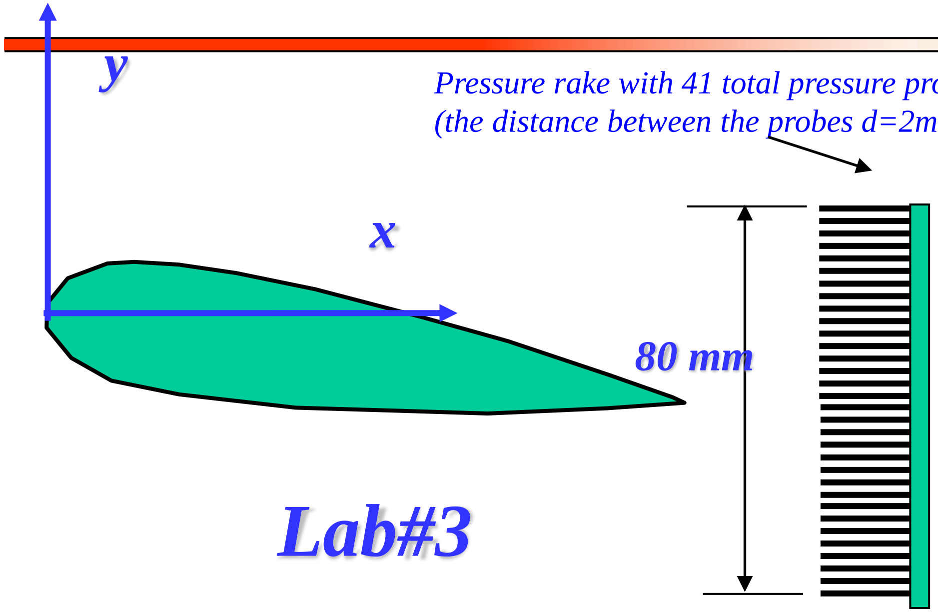
$$C_D = \frac{D}{\frac{1}{2}\rho U_\infty{}^2 C} = \frac{\rho U^2{}_\infty \int_2 [\frac{U(y)}{U_\infty}(1-\frac{U(y)}{U_\infty})]dA_2}{\frac{1}{2}\rho U_\infty{}^2 C}$$

$$\Rightarrow C_D = \frac{2}{C}\int_2 [\frac{U(y)}{U_\infty}(1-\frac{U(y)}{U_\infty})]dy$$

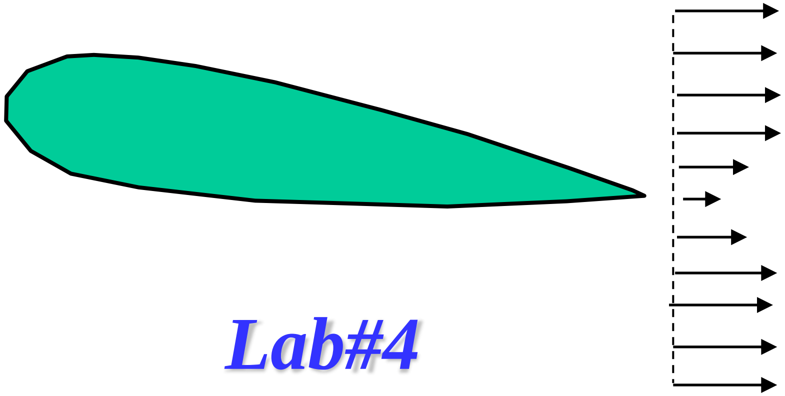


Pressure rake with 41 total pressure probes (the distance between the probes d=2mm)

Lab 07: Hot wire measurements in the wake of an airfoil



Lab#3



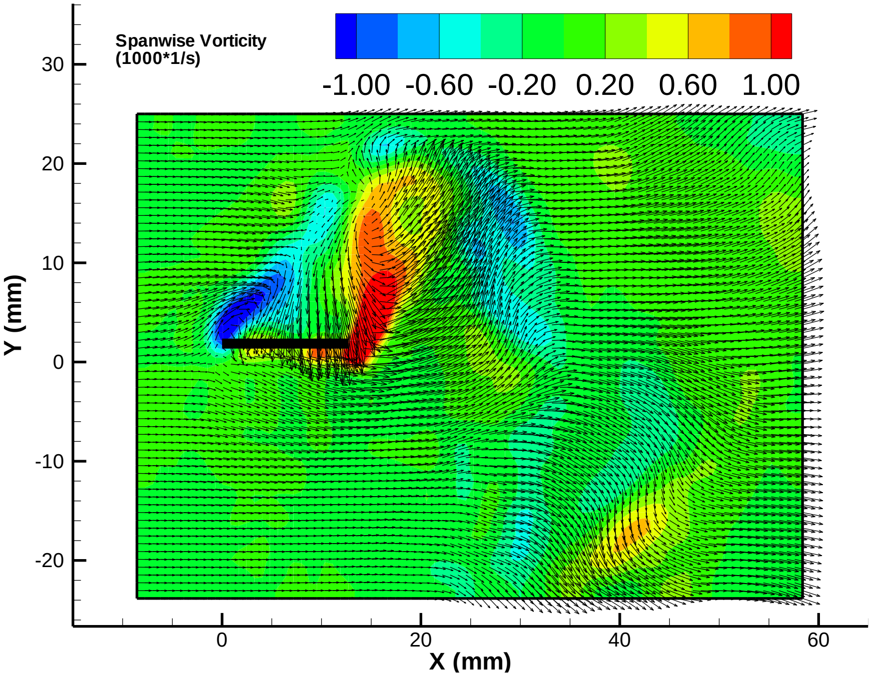
Lab#4

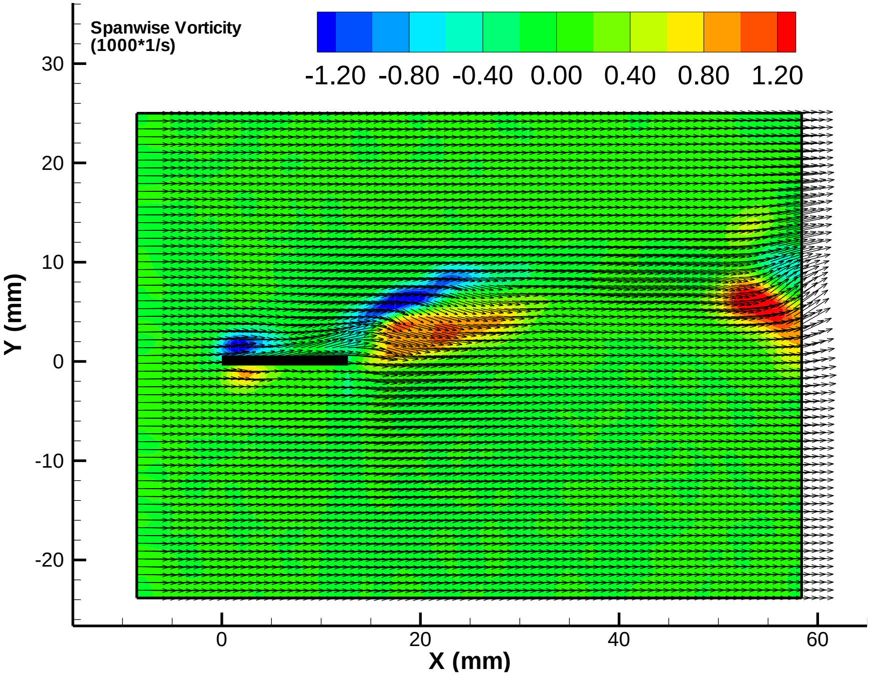
Hotwire probe

Test conditions:

Velocity:	*V=15 m/s*
Angle of attack:	*AOA=0, and 12 deg.*
Date sampling rate:	*f=1000Hz*
Number of samples:	*10,000 (10s in time)*
No. of points:	*20~25 points*
Gap between points:	*~0.2 inches*

AerE343L Lab#6: PIV Measurements of a Flapping Wing

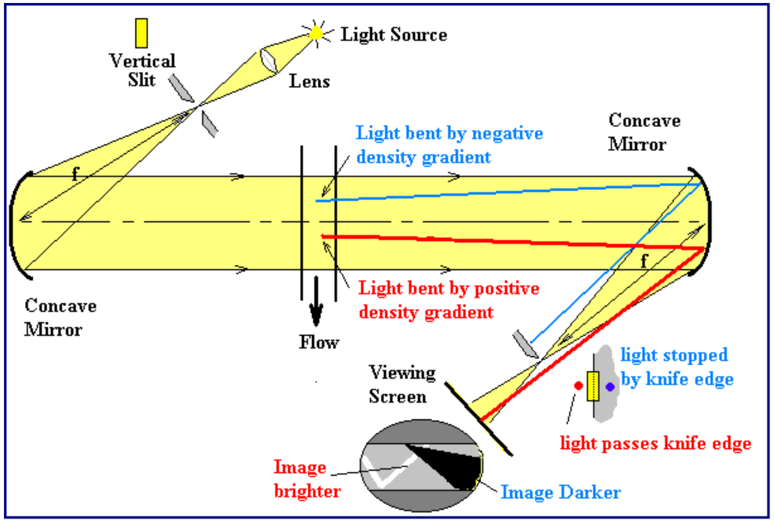


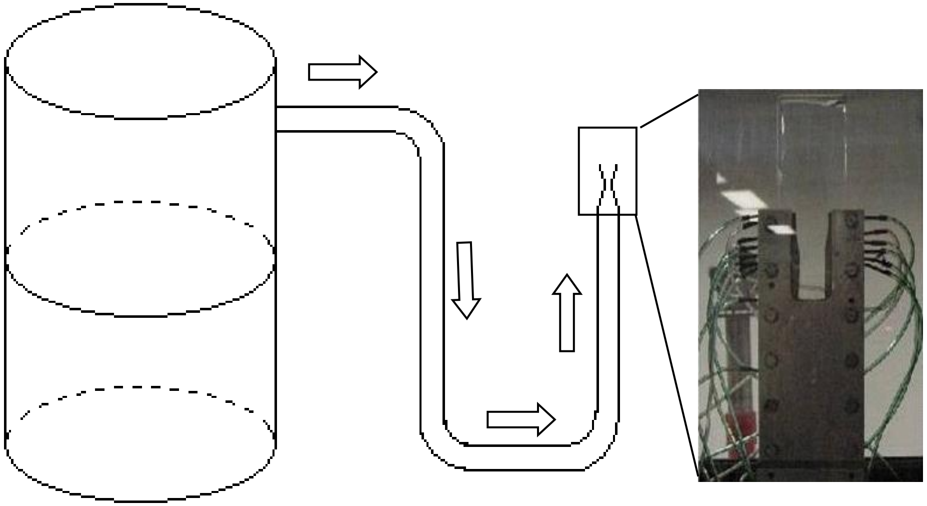


Flapping frequency:	*f = 60Hz*
Chord length:	*C = 12.7mm*
Wing span:	*L = 76.7 mm*
Flow velocity:	*V = 1.44 m/s*

Flapping frequency:	*f = 60Hz*
Chord length:	*C = 12.7mm*
Wing span:	*L = 76.7 mm*
Flow velocity:	*V = 6.36 m/s*

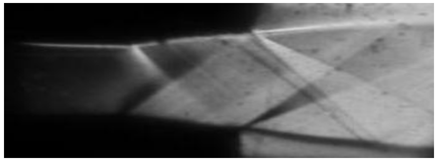
Lab#09: Visualization of Shockwaves using Schlieren technique





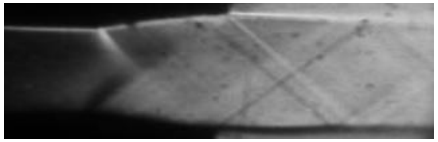
Tank with compressed air

Test section



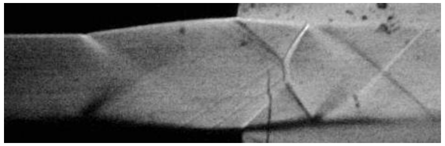
Under-expanded flow

⇩



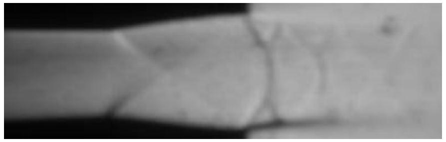
Flow close to 3rd critical

⇩



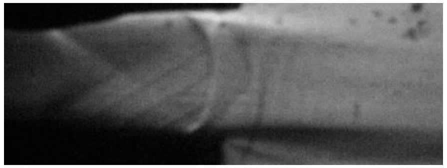
Over-expanded flow

⇩

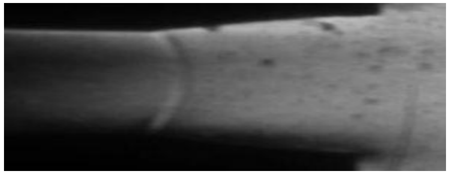


2nd critical – shock is at nozzle exit

⇩

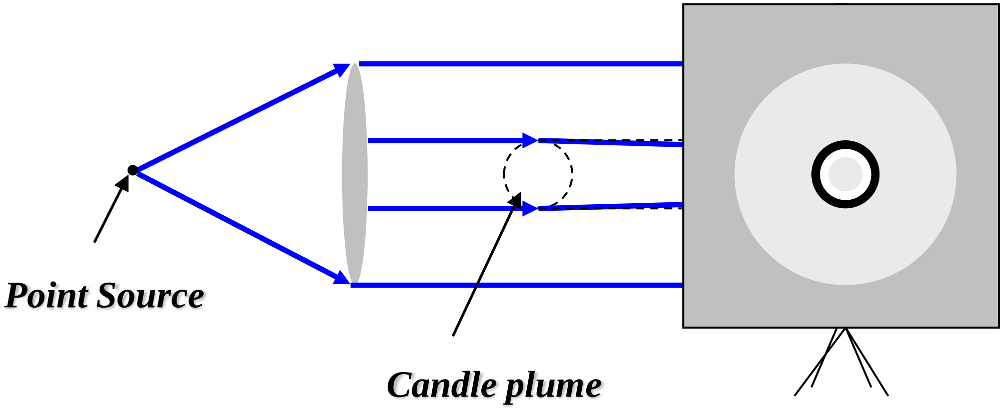


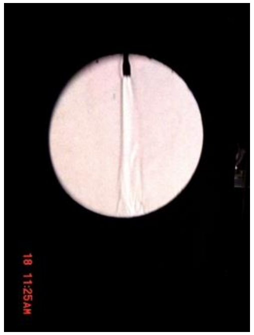
⇩

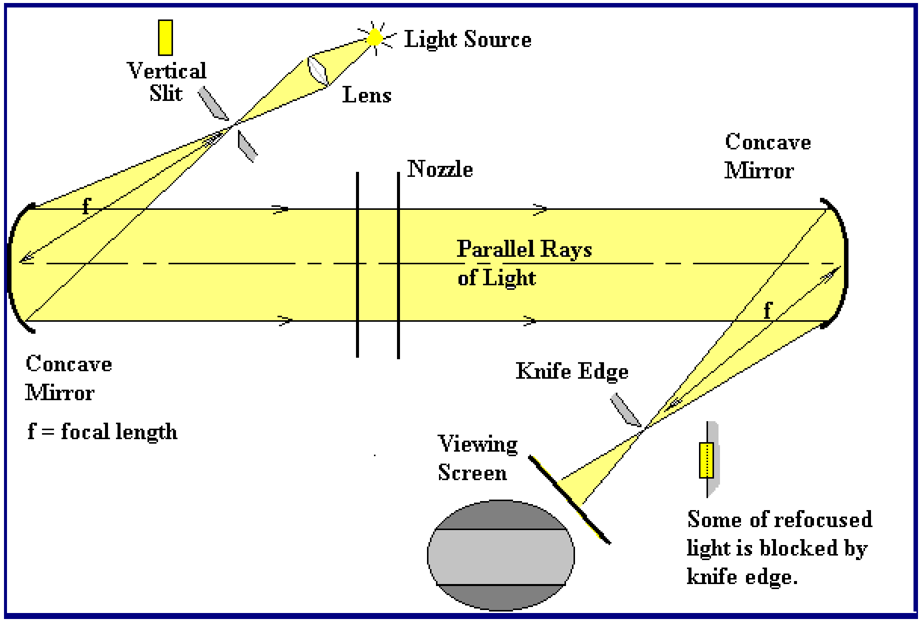


1st critical – shock is almost at the nozzle throat.

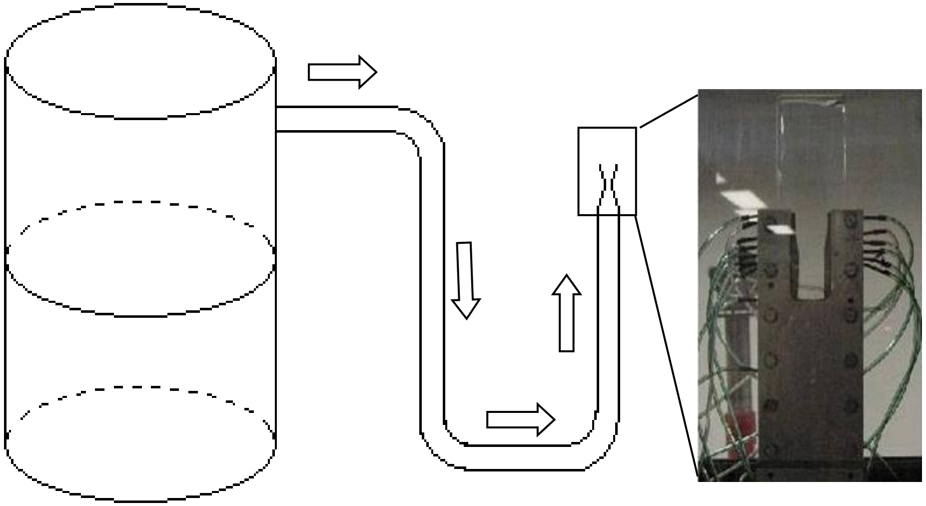
Lab#10: Set Up a Schlieren and/or Shadowgraph System to Visualize a Thermal Plume



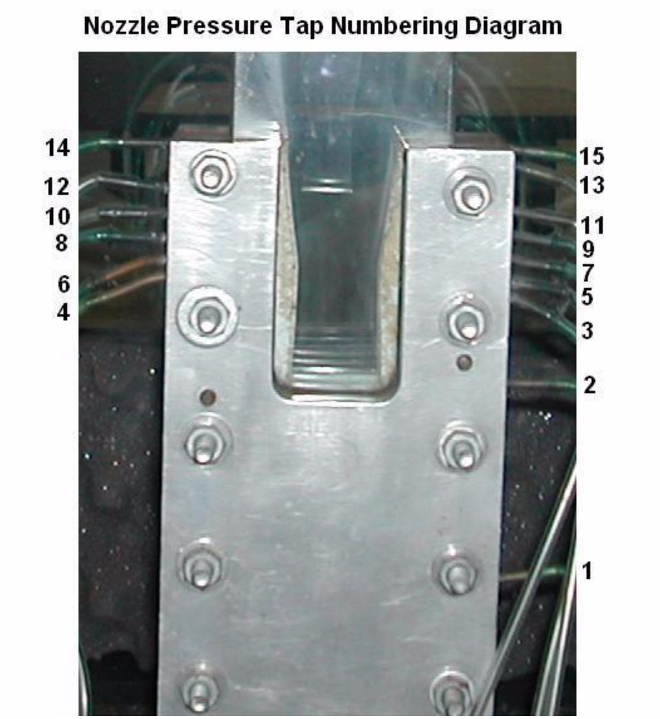




Lab#11: Pressure Measurements in a de Laval Nozzle

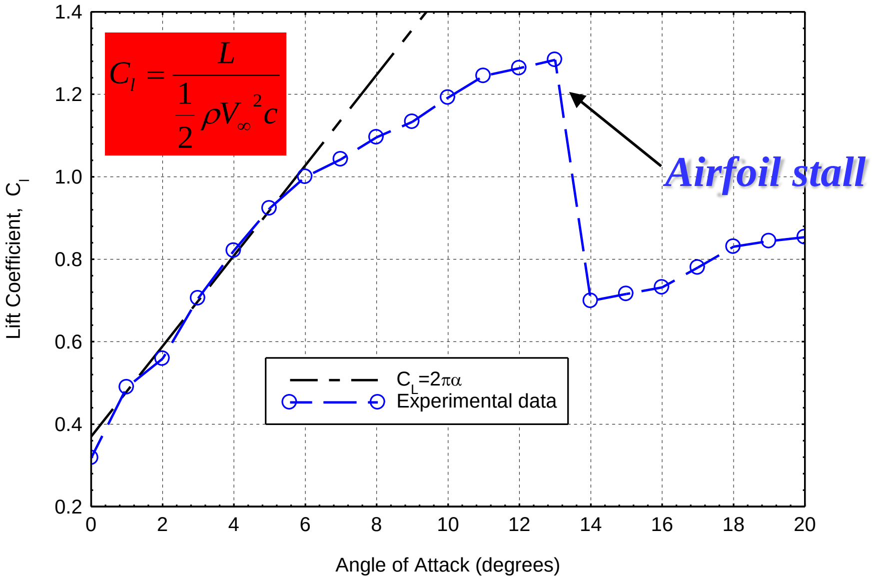

Tank with compressed air

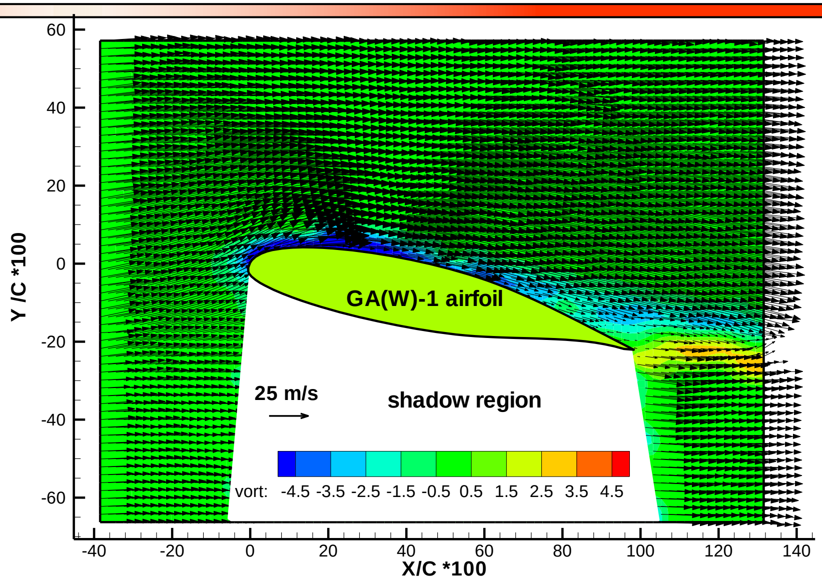
Test section


Nozzle Pressure Tap Numbering Diagram

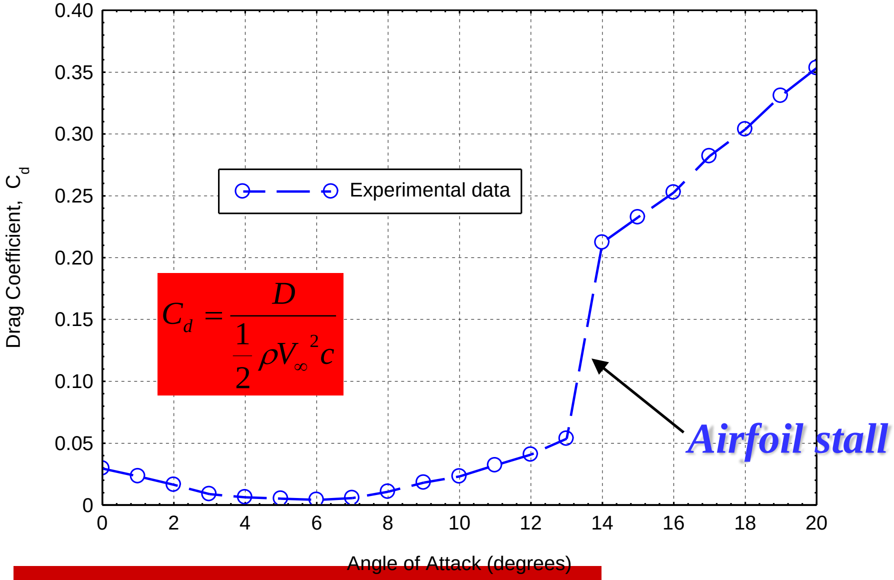
Tap No.	Distance downstream of throat (inches)	Area (Sq. inches)
1	-4.00	0.800
2	-1.50	0.529
3	-0.30	0.480
4	-0.18	0.478
5	0.00	0.476
6	0.15	0.497
7	0.30	0.518
8	0.45	0.539
9	0.60	0.560
10	0.75	0.581
11	0.90	0.599
12	1.05	0.616
13	1.20	0.627
14	1.35	0.632
15	1.45	0.634

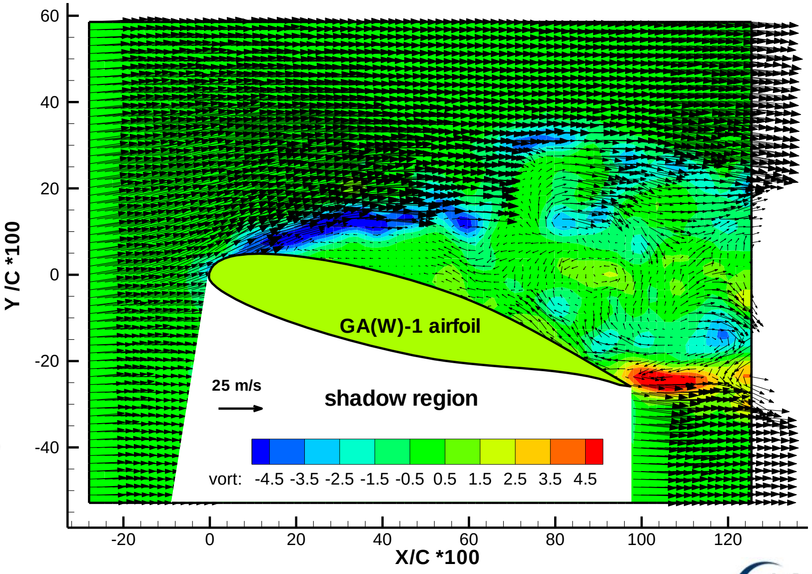
Lab#12: PIV measurements of the Unsteady Vortex Structures in the Wake of an Airfoil





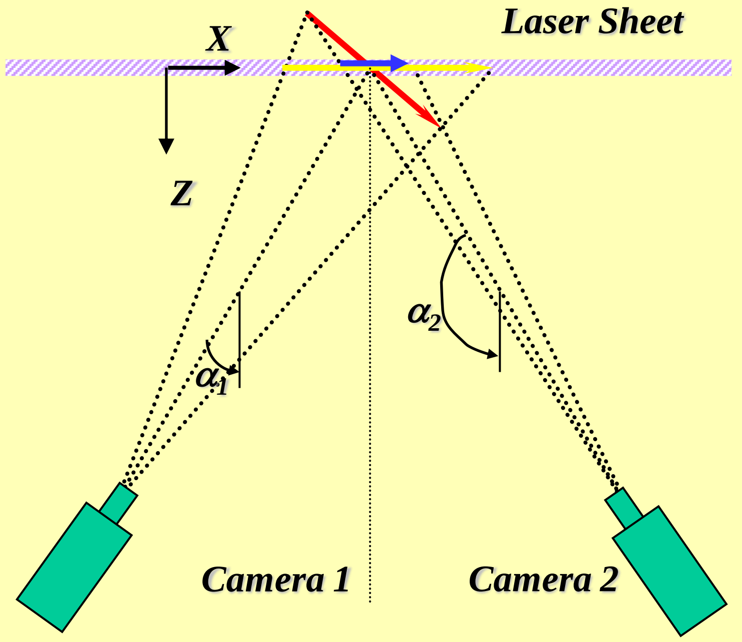
Before stall



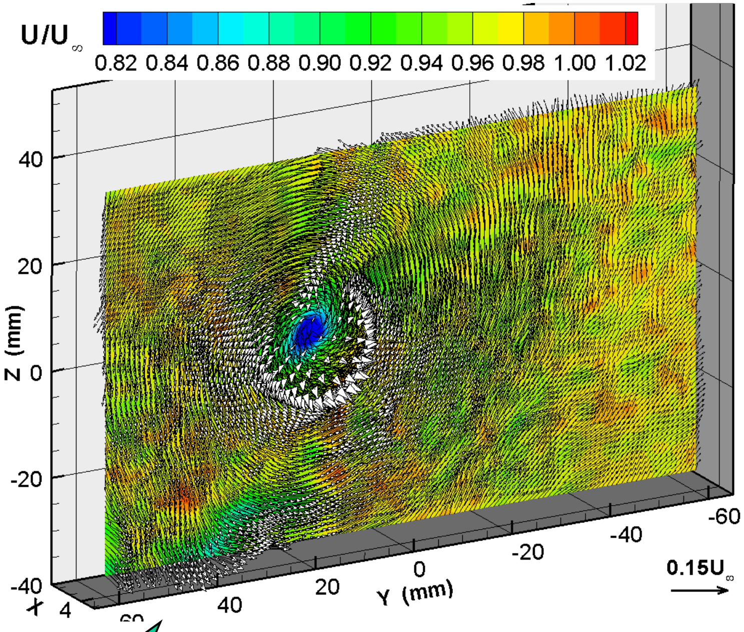


After stall

Lab#13: Stereoscopic PIV technique and Applications

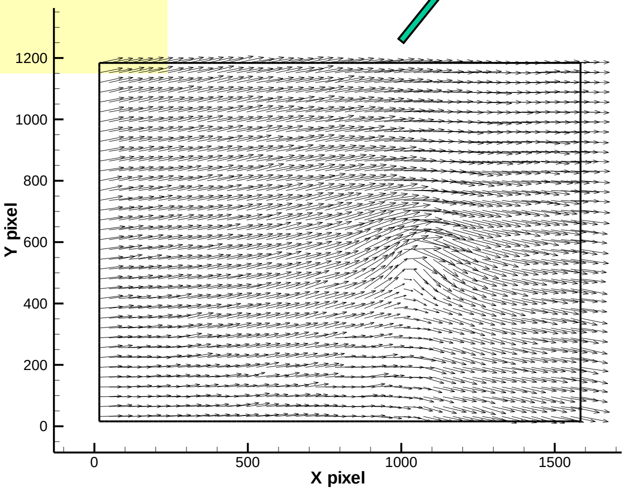


Stereo PIV technique

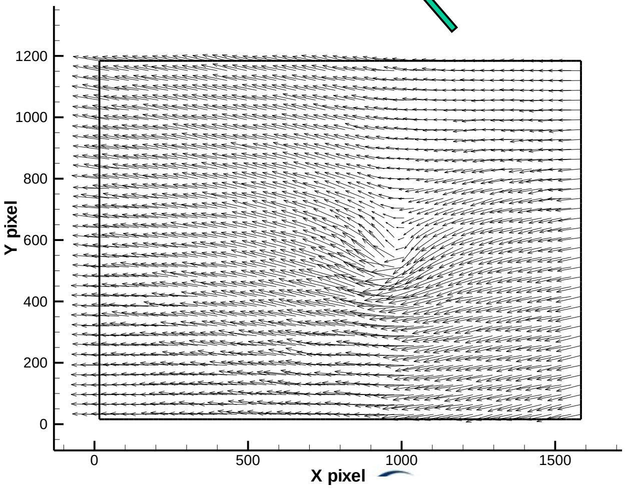


$$Re_C = 52{,}000; \alpha = 5.0 \text{ deg.}$$

X/C =4.0



Displacement vectors in left camera



Displacement vectors in right camera