Wind Tunnel Experiment

MAE 171A/175A

Objective:

Measure the Aerodynamic Forces and Moments of a Clark Y-14 Airfoil
Under Subsonic Flow Conditions

Measurement Techniques

- Pressure Distribution on Airfoil
- Drag from Momentum Loss Measured with a Wakefield Flow Array
- Direct Measurement with Mechanical Force

Procedure

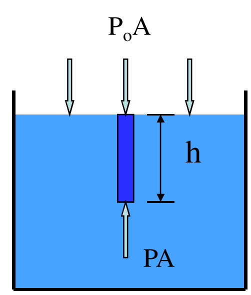
- Calibrate Tunnel w/ Pitot-Static Tube
- Measure Pressure Distribution on Airfoil
  -Different Flow Speeds & Angle-of-Attack
- Wakefield Measurement of Drag
- Mechanical Force Balance

Review of Hydrostatic Pressures

- Demonstration of pressure increase with depth
- Weight of the column $W=mg=\rho Ahg$
- Weight is supported by the net pressure $=(P-P_o)A$

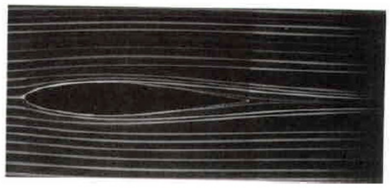
⇒ $P=P_o+\rho hg$

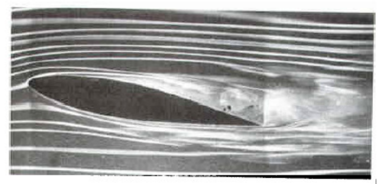
- Pressure increases with depth
- All points at a given depth are at the same pressure



Review of fluid motion

- The motion of fluid depends on the Reynolds No.
  - Laminar
  - Turbulent





- The laminar flow may be presented by streamlines
- When the fluid velocity is large or when the fluid encounters most obstacles, the flow becomes turbulent

Describing Fluid Behavior at Isothermal Conditions

- Conservation of Mass
- Newtons Second Law of Motion

Conservation of Mass

$$\frac{\partial \rho}{\partial t} + \vec{\nabla} \cdot (\rho \vec{w}) = 0$$

ρ- density
$\vec{w}$- velocity
t - time

$$\vec{\nabla} = \vec{i}\,\frac{\partial}{\partial x} + \vec{j}\,\frac{\partial}{\partial y} + \vec{k}\,\frac{\partial}{\partial z}$$

Constant density:

$$\nabla \cdot \vec{w} = 0$$

Note: This is valid for unsteady flow

Newton's Second Law – Euler's Equation

$$\rho \frac{D\vec{w}}{Dt} = \rho \frac{\partial \vec{w}}{\partial t} + \rho(\vec{w} \cdot \vec{\nabla})\vec{w} = -\vec{\nabla} p + \rho \vec{F}$$

p – pressure
$\vec{F}$ - body force per unit mass

Assume body force is due to gravity, and it is conservative

$$\vec{F} = -g\vec{\nabla} z$$

g – acceleration due to gravity

Euler's Equation

Vector identity:

$$(w\cdot\nabla)w=\tfrac{1}{2}\vec{\nabla}(\vec{w}\cdot\vec{w})-\vec{w}\times\nabla\times\vec{w}$$

Thus

$$\rho\frac{\partial\vec{w}}{\partial t}+\frac{1}{2}\rho\nabla(\vec{w}\cdot\vec{w})+\nabla p+\rho g\vec{\nabla}z=\rho\vec{w}\times\nabla\times\vec{w}$$

Constant density

$$\frac{\partial\vec{w}}{\partial t}+\nabla\left[\frac{1}{2}\vec{w}\cdot\vec{w}+\frac{p}{\rho}+gz\right]=\vec{w}\times\nabla\times\vec{w}$$

Bernoullis Equation – Steady Rotational Flow

Consider Flow Along a Streamline

$$\left\{\vec{\nabla}\left[\tfrac{1}{2}\vec{w}\cdot\vec{w}+\frac{p}{\rho}+gz\right]=\vec{w}\times\vec{\nabla}\times\vec{w}\right\}\cdot d\vec{S}$$

Along a streamline

$$\tfrac{1}{2}\vec{w}\cdot\vec{w}+\frac{p}{\rho}+gz=const$$

Bernoullis Equation – Unsteady Irrotational Flow

$$\nabla \times \vec{w} = 0 \qquad \vec{w} = \vec{\nabla}\phi$$

$$\nabla\left[\frac{\partial \phi}{\partial t} + \frac{1}{2}\vec{w}\cdot\vec{w} + \frac{p}{\rho} + gz\right] = \vec{w}\times\vec{\nabla}\times\vec{w} = 0$$

$$\frac{\partial \phi}{\partial t} + \frac{1}{2}\vec{w}\cdot\vec{w} + \frac{p}{\rho} + gz = const$$

Applications of Bernoulli’s Equation

- We Measure Flow Velocity Using Bernoulli’s Eqn:

$$P_a + \frac{1}{2}\rho_a U_a^2 = P_b + \frac{1}{2}\rho_b U_b^2$$

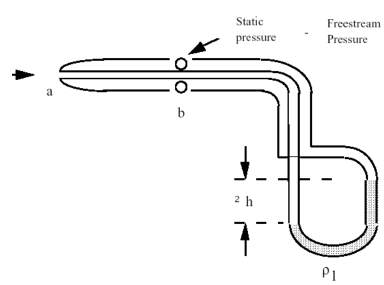
where:

$$U_a = 0, \; U_b = U_\infty$$

$$P_a - P_b = \frac{1}{2}\rho_\infty U_\infty^2 = q_\infty \quad \text{or} \quad P_a - P_b = \rho_1 \cdot \Delta h \cdot g$$

and:

$$U_\infty = \left(\frac{2(P_a - P_b)}{\rho_\infty}\right)^{1/2} \quad \text{or} \quad U_\infty = \left(\frac{2\rho_1 \Delta h\, g_e}{\rho_\infty}\right)^{1/2}$$

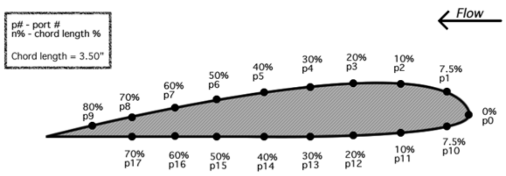


Pitot Probe: Measurement of Fluid Velocity

Δh is determined experimentally

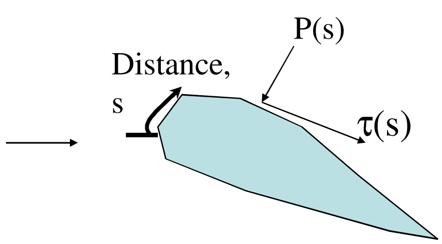
Pitot tube was invented by a Frenchman Henry Pitot in 1732

Pressure Distribution



- Pressure Taps Located Around Airfoil Surface
- Provide P(**x**) Data
- Integrate This Data Over Airfoil Surface to Find Net Force Vector & Moment….

Aerodynamic Forces in Airfoil

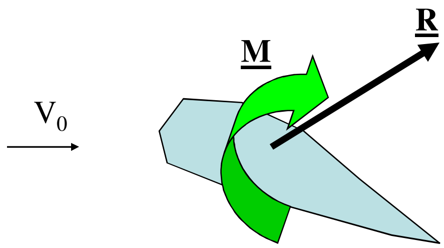


- Pressure Distribution on Body Surface Given as P(s)
- Shear Stress on Body Surface given as τ(s)
- P acts normal to surface

  τ acts tangential to surface

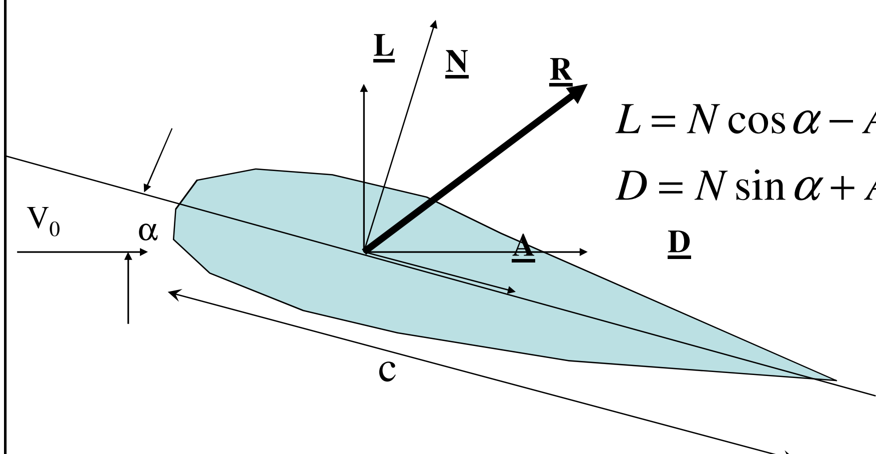
Both have Force/Area Units

Integrating P and τ Distributions Gives Force & Moments on Airfoil



- Total Force, R, Can Be Resolved into Lift Force, L and Drag Force D
  - L acts perpendicular to V0
  - D acts parallel to V0

Lift & Drag Forces



$$L = N\cos\alpha - A\sin\alpha$$

$$D = N\sin\alpha + A\cos\alpha$$

N, A - Normal, Axial components w/r/t chord
D,L - Axial, Normal components w/r/t free stream V0

Integrate Pressure Over Surface to Find Net Force:

Dimensionless Pressure Coefficient:

$$C_p = \frac{p - p_{ref}}{\frac{1}{2}\rho U^2}$$

Normal Force Coefficient:

$$C_n = \frac{N}{\frac{1}{2}\rho V_0^2 A_{span}} \approx \frac{1}{c}\int_0^c (C_{p_L} - C_{p_U})dx$$

Neglecting Skin Shear Stress Effects

Determine Lift Coefficient from Normal Force Coefficient

- Use the Geometry to Find

$$L = N\cos\alpha - A\sin\alpha$$

- Usually A<<N, Thus Can Approximate

$$C_L \approx C_N \cos\alpha$$

- Note That the Assumption A<<N Implies Drag Force is Small (I.e. we are taking C_d~0).

Determine Pitching Moment Coefficient from Pressure Coefficient Distribution

- Use the Geometry to Find

$$C_{m_{ref}} = \frac{1}{c^2}\int_0^c (C_{p_U} - C_{p_L})(x - x_{ref})\,dx$$

- Conventional X_{ref} is Quarter-chord Location

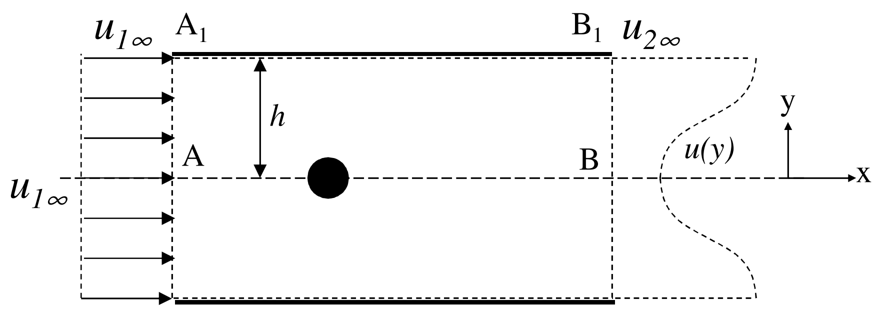
- Center-of-Pressure Location Is Then Given as

$$\frac{X_{cp}}{c} = -\frac{C_{M_{LE}}}{C_N}$$

Part 2

- Drag from Momentum Loss Measured in Wake with Pressure Array

Drag Coefficient



- incompressible

Drag Coefficient

<u>Mass Conservation</u>

<u>Cross Section:</u> (Rate of Flow)

$$AB = 0$$

$$AA_1 = \rho b \int_0^h u_{1\infty} dy = \rho b h u_{1\infty}$$

$$BB_1 = -\rho b \int_0^h u dy$$

$$A_1B_1 = -\rho b \int_0^h (u_{1\infty} - u) dy$$

Drag Coefficient

Equation of Motion – steady Flow:

$$\int\int\int [\nabla \cdot (\rho \vec{w}\vec{w})] dV = Drag$$

Reynolds Transport Theorem

$$\iiint \vec{\nabla} \cdot \vec{F} dV = \iint \vec{F} \cdot \vec{n} dA$$

If static pressure on AA_1, BB_1 are same

Drag Coefficient

Equation of Motion

Cross Section	$\int \rho \vec{w}\vec{w} \cdot n dA$
AB	0
AA_1	$\rho b h u_{1\infty}^2$
BB_1	$-\rho b \int_0^h u^2 dy$
A_1B_1	$-\rho b \int_0^h u_{1\infty}(u_{1\infty} - u) dy$

$$Drag = 2\rho b \int_0^h u(u_{1\infty} - u) dy$$

$$= 2\rho b u_{1\infty}^2 \int_0^h \frac{u}{u_{1\infty}} \left[1 - \frac{u}{u_{1\infty}}\right] dy$$

Drag Coefficient

Drag on Cylinder:

Per unit length (b = 1)

$$Drag = 2\rho b u_{1\infty}^2 \int_0^h \frac{u}{u_{1\infty}}\left[1 - \frac{u}{u_{1\infty}}\right] dy$$

The Drag Coefficient C_D

- Drag Coefficient is computed from drag, D:

$$C_d = \frac{D}{\frac{1}{2}\rho V_0^2 A_{span}}$$

- Use Previous Expression for Drag to Find Cd From Momentum Analysis:

$$C_d = \frac{Y_w}{c} - \frac{1}{q_\infty c}\int_{-\frac{Y_w}{2}}^{\frac{Y_w}{2}} q \, dy$$

where

$$q = \frac{1}{2}\rho V^2(y)$$

Y_w ~ Wakefield array width

Wakefield Procedure

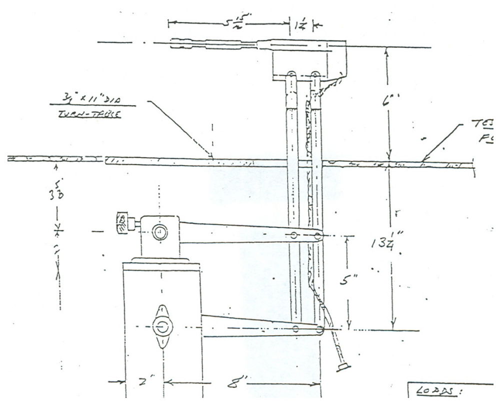
- Operate Tunnel at Desired Flowspeed & Airfoil Angle-of-Attack
- Make Sure Wakefield Array Covers Entire Wake
- Gather q(y) data
- Use Theory to Find Drag Force, Coefficient

Part 3

- Direct Measurement with Mechanical force Balance

Mechanical Force Balance

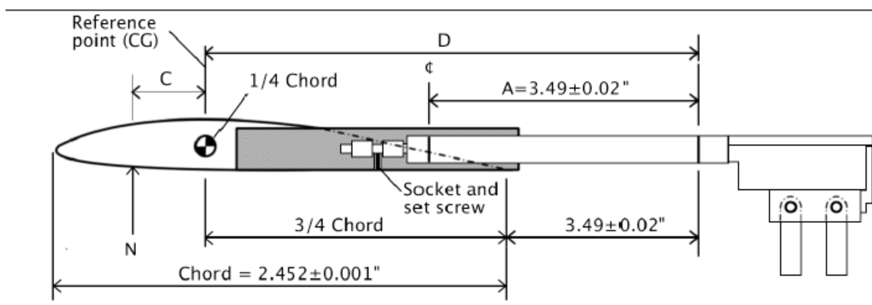
Force Balance Mechanism



- Mount Airfoil on Small "Sting", or cylinder holder
- Sting Attaches to Load Frame
- Strain Gauges Used to Measure Forces & Moments on Sting Assembly

Mechanical Force Balance

Airfoil & Sting Detail



Airfoil Span (overall length of airfoil) = 9.8125±0.0625"
¢ - Balance center
(Marked on wing section)

Mechanical Force Balance

- The lift, drag, and pitching forces on the airfoil can be calculated from a force balance measurements of the axial force A', normal force N', and pitching moment P' relative to the sting support on the balance.
- The values of A', N', and P' are measured from strain gauge bridges on the force balance and are not independent.
- Compensate for this interaction between the measured values with matrix:

$$N = N'*.9504-A'*.0082-P'*0.0161$$
$$A = N'*.0608+A'*.5912$$
$$P= -N'*.1336+A'*.0119+P'*1.182$$

References

1. John D. Anderson, “Fundamentals of Aerodynamics”, 2nd Ed., pp. 195-200 and pp. 228-236, McGraw Hill 1991.