Can Lift Be Explained?

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Outline

- The Challenge
- Issues
- Experimental Numerical Model
- Influenced Flow
- Role of Coanda Effect
- An Explanation ?
- Closure

The Challenge

- Explain how lift is generated by an airfoil in a way that:
  - uses everyday terms;
  - uses concepts that are accessible to scientifically literate people;
  - is factually true; and
  - is fundamental in the sense that refined and improved understanding can follow from the explanation.

Delimitation

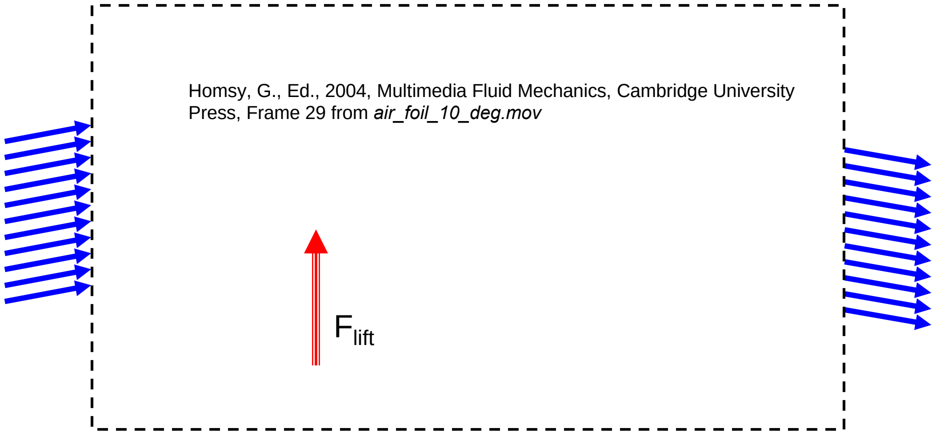
- Focus on:
  - thin airfoils;
  - steady, incompressible flow;
  - low angles of attack (attached flow);
  - two dimensional flow (neglect wing tip effects); and
  - lift phenomena (as opposed to drag phenomena).

Two Bases for Understanding

Nakayam, Y., Ed., 1988, Visualized Flow: Fluid motion in basic and engineering situations revealed by flow visualization., Japan Society of Mechanical Engineers, Pergamon Press, Oxford, Figure 155 pg. 86.

- Conservation of Linear Momentum
- Net Force due to Pressure (*and wall shear*) Stresses

Linear Momentum Explanation



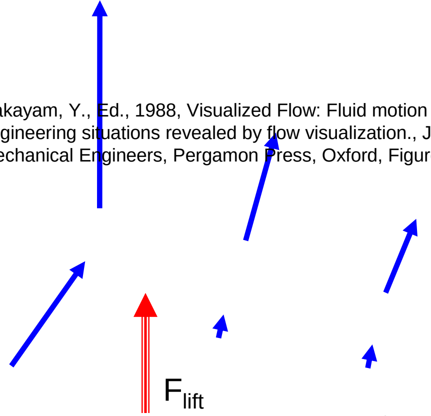
Homsy, G., Ed., 2004, Multimedia Fluid Mechanics, Cambridge University Press, Frame 29 from *air_foil_10_deg.mov*

Linear Momentum Explanation: Issues

Homsy, G., Ed., 2004, Multimedia Fluid Mechanics, Cambridge University Press, Frame 29 from *air_foil_10_deg.mov*

- Amount of upturn versus downturn
  - explaining the upturn
- Amount of fluid influenced (turned) by the airfoil
  - split of influenced fluid to travel over the top or the bottom of the airfoil
  - local versus distant influences
- Influence of airfoil shape on lift (*and drag*)

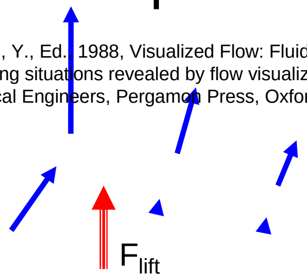
Pressure Explanation



Nakayam, Y., Ed., 1988, Visualized Flow: Fluid motion in basic and engineering situations revealed by flow visualization., Japan Society of Mechanical Engineers, Pergamon Press, Oxford, Figure 155 pg. 86.

$$C_p \equiv \frac{p - p_\infty}{\frac{1}{2}\rho V_\infty^2} = \left(1 - \frac{V^2}{V_\infty^2}\right)$$

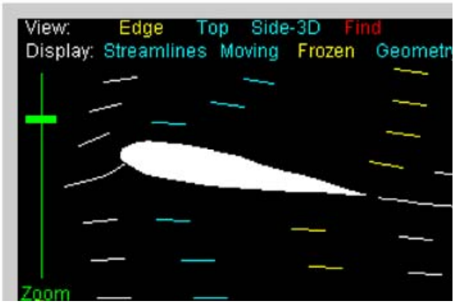
Pressure Explanation: Issues



Nakayam, Y., Ed., 1988, Visualized Flow: Fluid motion in basic and engineering situations revealed by flow visualization., Japan Society of Mechanical Engineers, Pergamon Press, Oxford, Figure 155 pg. 86.

- Reason for low pressure on top surface
  - connection to high speed over top surface
- Pressure recovery on top and bottom surfaces
  - centre of pressure location
  - influence of airfoil thickness

Plausible Explanation: Path Length



- Path over top of airfoil is longer then path over bottom of airfoil
- Transit times are identical
- Speed on top is greater then on bottom
- Pressure on top is less then on bottom (Bernoulli)

Plausible Explanation: Coanda Effect

Van Dyke, M., 1982, An Album of Fluid Motion, Parabolic Press, Palo Alto, California, Figure 169 pg. 99.

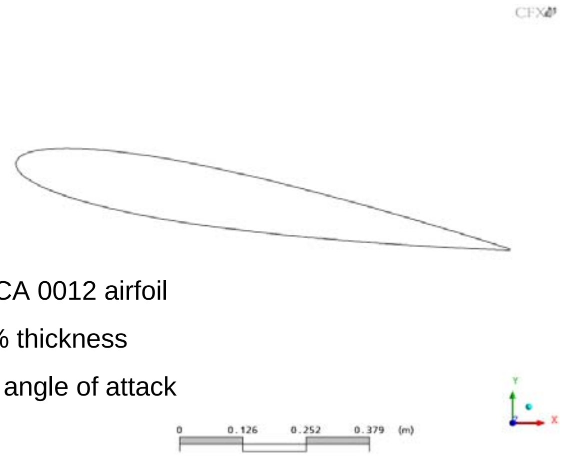
Van Dyke, M., 1982, An Album of Fluid Motion, Parabolic Press, Palo Alto, California, Figure 171 pg. 99.

- Fluid is entrained into shear layer of fluid jet
- Presence of wall restricts the entrainment flow and creates a low pressure region adjacent to the jet exit
- Jet deflects into the low pressure region
- Used to explain flow over top of the airfoil

Summary of Issues

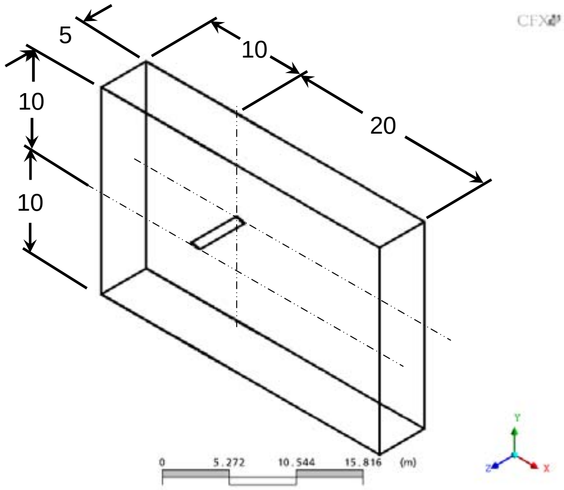
- Momentum Explanation
  - – cause of upturn in the approach flow ???
  - – amount of influenced flow ???
- Pressure Explanation
  - – role of shear layer in creating flow over the top (Coanda effect) ???
  - – causes of pressure distribution ???

Numerical Model: Geometry 1

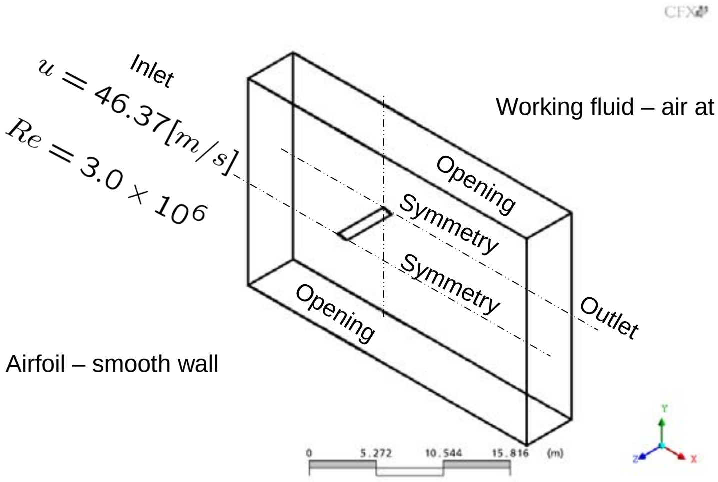


- NACA 0012 airfoil
- 12% thickness
- 10° angle of attack

Numerical Model: Geometry 2



Numerical Model: BC



Working fluid – air at 25°C

Airfoil – smooth wall

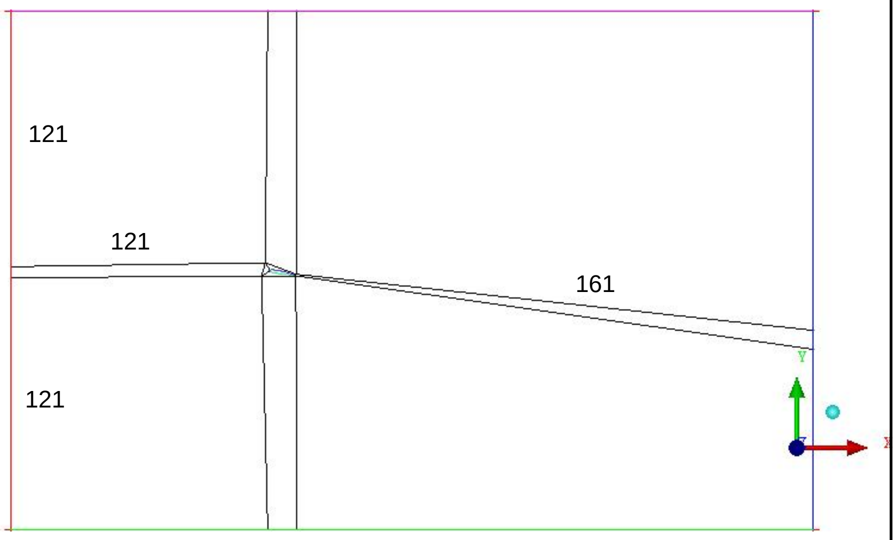
Numerical Model: Flow Model

- Shear Stress Transport (SST) two equation eddy viscosity model of turbulence
- In wake, outer layer, and freestream: conventional k-ε model
- Close to wall:
  - $\omega = \varepsilon / k$ for turbulent length scale
  - $\tau_{xy} = a_1 k$ (*consistent with equilibrium transport of Reynolds stress*)
- Farfield turbulent intensity is 1%

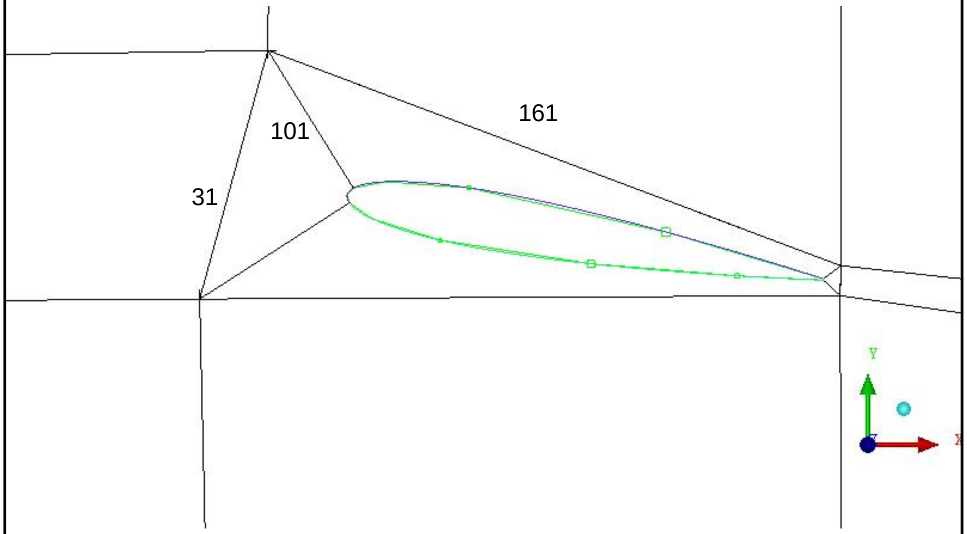
Numerical Model: Numerics

- Preliminary Mesh:
  - structured hexahedral mesh (O-grid topology around airfoil and H-grid topology in domain)
  - 152,900 nodes / planes times 2 planes
  - y^+ varies between 4 and 132
  - some results with significantly coarser meshes
- Second order (locally bounded) advection scheme based on a least squares gradient reconstruction
- Normalized residuals of momentum and mass equations reduced to at least 5×10^{-4}
- Global domain imbalances below 1×10^{-4}

Numerical Model: Mesh Details 1

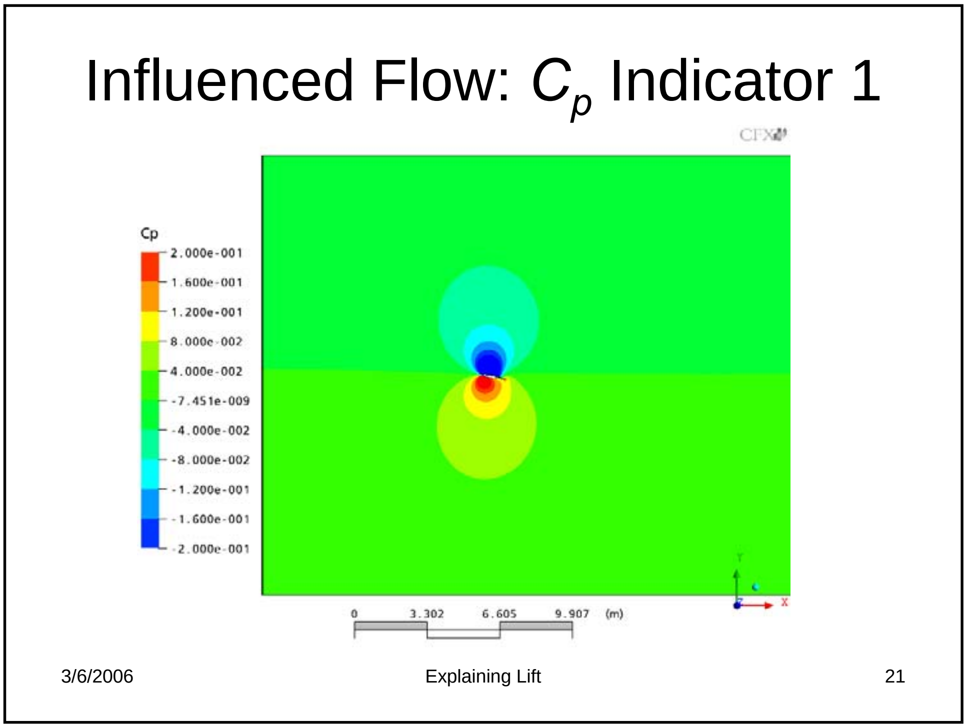


Numerical Model: Mesh Details 2

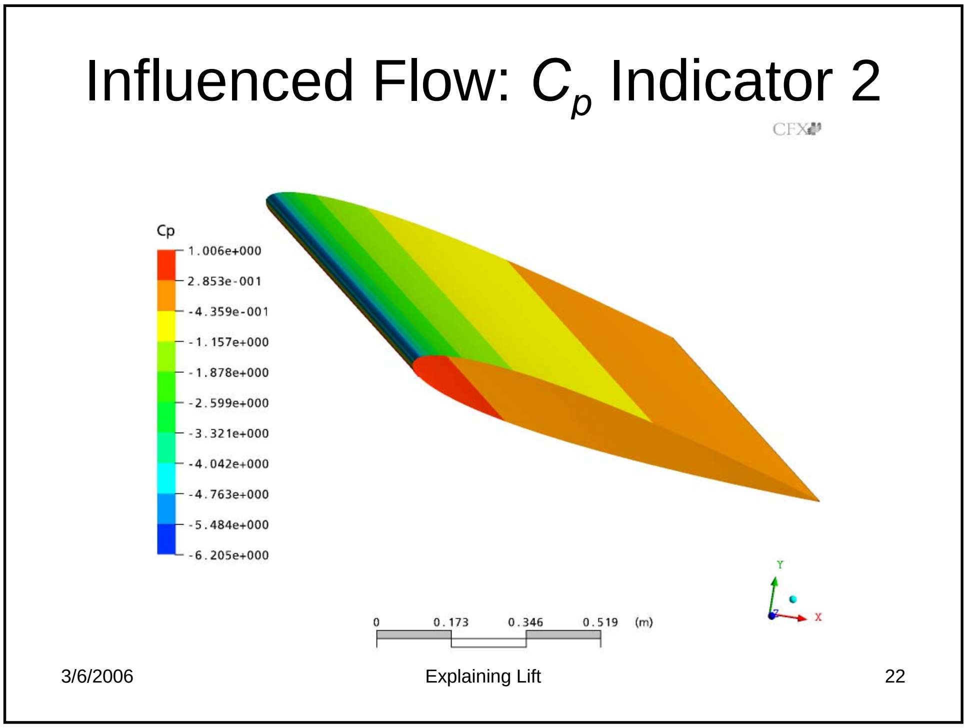


Numerical Model: Experiments

- Study of the flow influenced by the presence of the airfoil
- Comparison of no-slip and slip flow conditions on airfoil surface to assess the importance of the Coanda effect

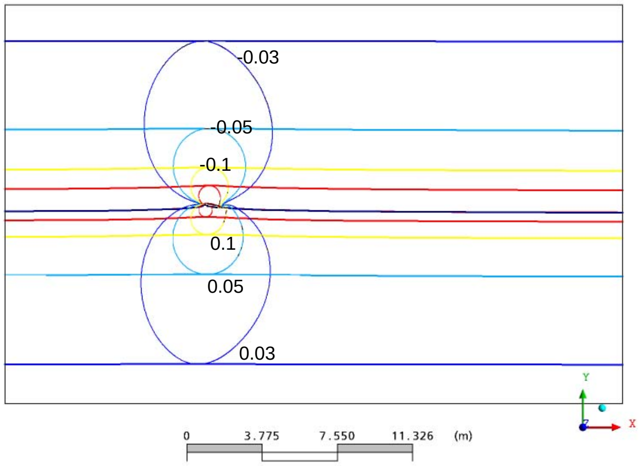


Influenced Flow: C_p Indicator 1

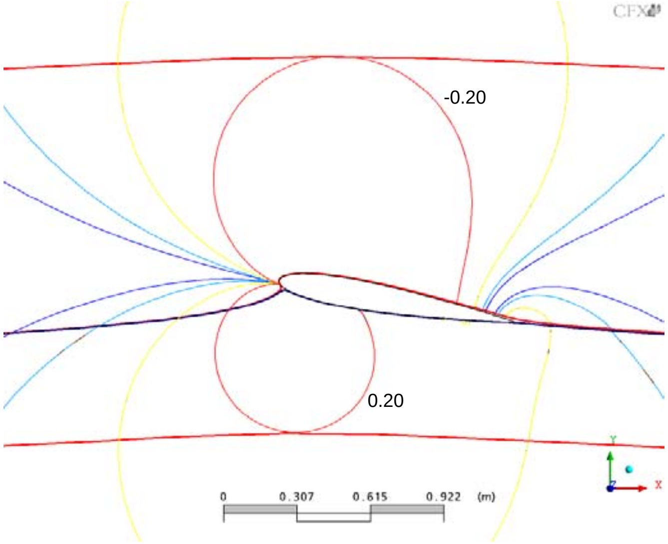


Influenced Flow: C_p Indicator 2

Influenced Flow: C_p Indicator 3



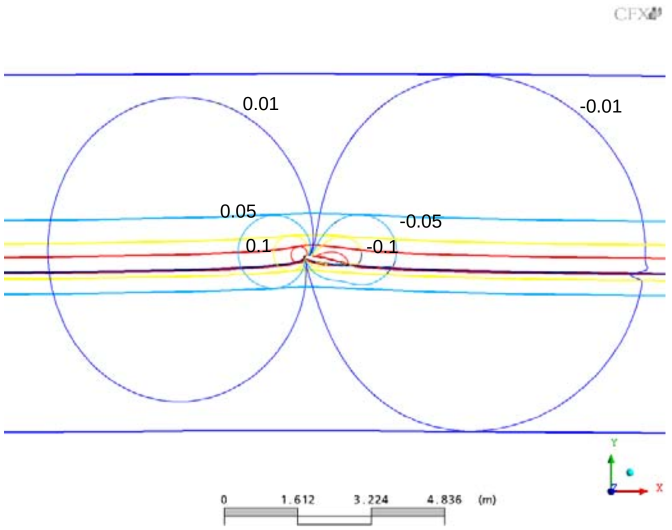
Influenced Flow: C_p Indicator 4



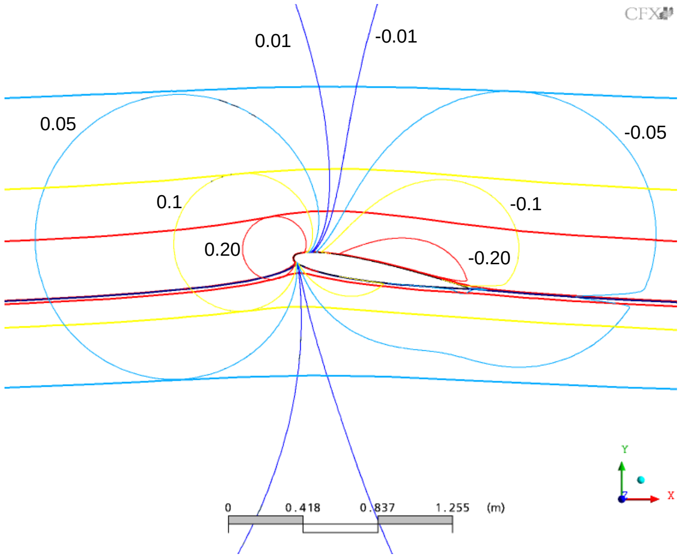
Influenced Flow: C_p Indicator 5

C_p	m_{top}/m_{bot}	m_{top}/m
±0.20	2.44	0.71
±0.10	1.63	0.62
±0.05	1.27	0.56
±0.03	1.11	0.53

Influenced Flow: $\tilde{v}$ Indicator 1



Influenced Flow: $\tilde{v}$ Indicator 2



Influenced Flow: $\tilde{v}$ Indicator 3

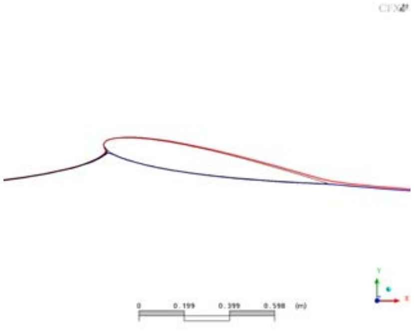
$\tilde{v}=v/U_0$	m_{top}/m_{bot}	m_{top}/m
±0.20	16.50	0.94
±0.10	4.13	0.81
±0.05	2.38	0.70
±0.01	1.24	0.55

Influenced Flow: Summary

- C_p Conclusions:
  - – far field pressure changes on top and bottom are closely balanced
  - – near field pressure drop on top is more dominant then pressure rise on bottom
- $\tilde{v}$ Conclusions:
  - – far field shows that downwash dominates and is balanced between top and bottom
  - – near field shows that upwash dominates and mostly flows over the top

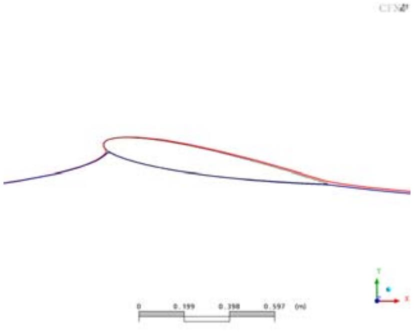
Coanda Effect 1

No-slip surface



y_{divide} = -0.351

Slip surface



y_{divide} = -0.380

Coanda Effect 2

Zone/ Parameter	F_y [N] No-slip	F_y [N] Slip	F_x [N] No-slip	F_x [N] Slip
Nose	410	446	-605	-690
Top	4906	5342	246	253
Bottom	1496	1732	452	462
End	0	0	-2	0
Totals	6812	7520	92	24
$C_{L/D}$	1.07	1.18	0.014	0.004
Exp.	1.10	1.10	0.013	0.013

Coanda Effect: Summary

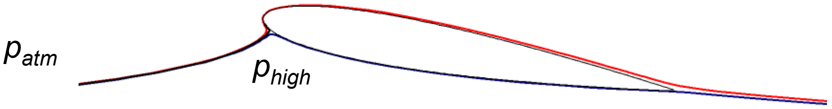
- With no shear layer around the airfoil the lift increases.
- As expected the drag decreases (*there is still a component of lift-induced drag*).
- Flow differences are minor except immediately adjacent to the airfoil.

An Explanation

1. Fluid fills the flow domain.
    - Follows from:
        - fundamental definition of a fluid = matter that cannot resist a shear stress without motion, and
        - fact that fluid cannot flow through a solid surface.
    - Consequently the flow follows the top and bottom surfaces of the airfoil.

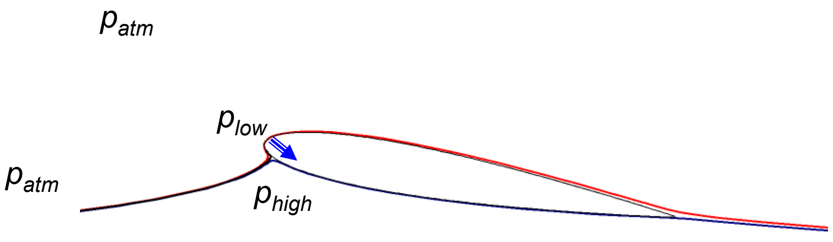
An Explanation

2. Stagnation pressure on nose
    - use stagnation velocity and Bernoulli



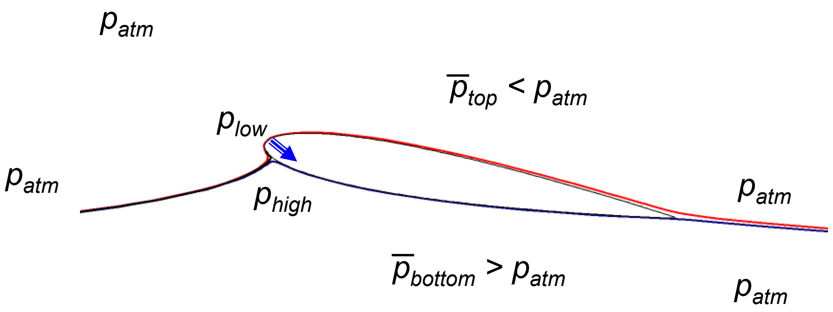
An Explanation

3. Centrifugal acceleration in flow over top of the nose.
   - pressure gradient normal to streamline balances centrifugal acceleration



An Explanation

4. Pressures of top and bottom flows match at trailing edge.
   - pressure close to atmospheric pressure

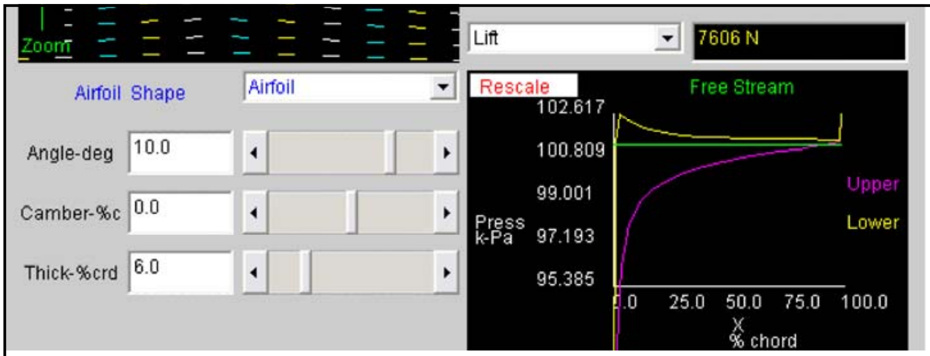


Comments

- H. Babinsky, 2003, How do wings work?, *Physics Education*, 38, pp. 497-503.
- Consistent with increased effect over the top – forward far field fluid will tend to flow over the top (lower pressure).
- Momentum explanation is a good place to start for absolute neophytes.

Unresolved Issue: Airfoil Thickness

- H. Babinsky: Increasing thickness doesn’t influence nose flow but does change curvature over back to decrease lift.
- With increasing thickness the curvature around the nose should decrease (*supported by FoilSim*)
- Experiment and *FoilSim* shows that for thin airfoils the lift increases with thickness



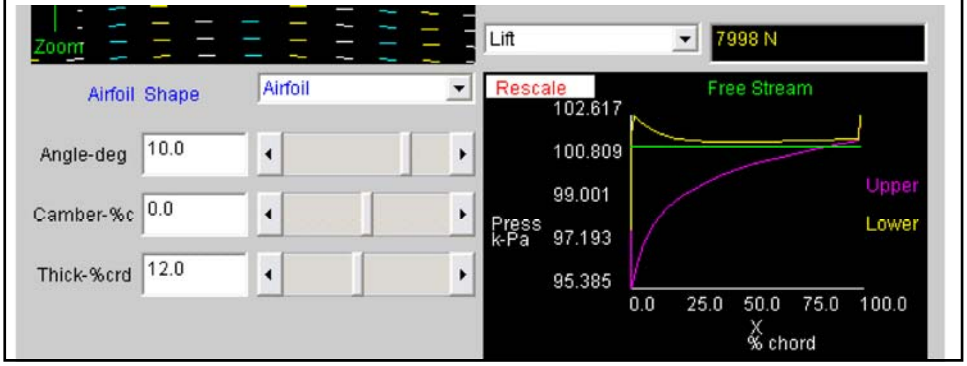
Lift 7606 N

Airfoil Shape: Airfoil

Angle-deg: 10.0

Camber-%c: 0.0

Thick-%crd: 6.0



Lift 7998 N

Airfoil Shape: Airfoil

Angle-deg: 10.0

Camber-%c: 0.0

Thick-%crd: 12.0

Airfoil Thickness

Bertin, J.J., and Smith, M.L., 1979, Aerodynamics for Engineers, Prentice Hall, Figure 4-10 pg. 124.

Closure

- Benefit of numerous discussions with Ali Ashrafizadeh, George Raithby, Johan Larsson, and the students of Shad Valley
- Complete description involves a multidensional (streamwise and cross-stream) consideration of pressure changes.
- Still a work in progress.

Bibliography

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