# *Lab 6: Lift and Bernoulli*

## *Bio427 — Biomechanics*

In this lab, we explore the flows and fluid dynamic forces on wings and other structures. We deploy force measurement techniques, wind meters, and a variety of wind tunnels to measure these forces for a range of structures.

Figure 1: 'what quality of air surround birds in flight? The air surrounding the bird is above thinner than the usual thinness of the other air, as below it is thicker than the same... in proportion to the velocity of the bird in its motion forward ...' *Sul volo degli Uccelli* (On the flight of birds) Leonardo da Vinci 1500

*Goals*

- Construct a physical model of, or simulate, a prairie dog burrow and use this model to observe induced flow due to the Bernoulli principle.
- Understand and measure lift forces
- Explore shape, aspect ratio and camber for wings
- Examine how lift varies with the angle of attack of wings

*Some useful constants for air at 20 C*

- Density $\rho = 1.2\,\mathrm{kg\,m^{-3}}$
- Dynamic viscosity $\mu = 1.9 \times 10^{-5}\,\mathrm{Pa\,s}$
- Kinematic viscosity $\nu = 1.5 \times 10^{-5}\,\mathrm{m^2 s^{-1}}$

*Some useful constants for water at 20 C*

- Density $\rho = 1000\,\mathrm{kg\,m^{-3}}$
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## *Conceptual Basis*

In this lab we will be examining two consequences of Bernoulli's principle. One is the idea that pressure differences introduced by conservation of mass can induce flow in animal structures (e.g. gills, burrows) saving energy by using environmental flows. Similarly, pressure differences can lead to lift forces, allowing animals to propel themselves in fluids.

## *Induced flow*

In lecture, we introduced Bernoulli's Principle as a fluid flow version of the law of energy conservation. Within some flow, the energy of a fluid particle with mass $m$ moving along some streamline with velocity $u$ will be the sum of its kinetic energy ($mu^2/2$), gravitational potential energy ($mgh$), and the less familiar flow energy, which is equal to the work done by the fluid as it moves and equal to the fluid pressure on the particle multiplied by its volume ($PV$) or, equivalently, the fluid pressure multiplied by the particle mass and divided by the fluid density ($Pm/\rho$). Bernoulli's equation states that energy must be conserved for a fluid particle moving within a flow, and so the sum of these three energies for that fluid particle must remain constant:

$$\frac{mu^2}{2} + \frac{Pm}{\rho} + mgh = \text{const.} \tag{1}$$

Typically in the analysis of fluid flows, however, we are often less interested in what happens to an individual particle within the fluid and more interested in characterizing the flow field. To this end, it is typically useful to rewrite Eqn. 1 by dividing both sides by $V = m/\rho$:

$$\frac{\rho u^2}{2} + P + \rho g h = \text{const.} \tag{2}$$

One critical assumption in Bernoulli's principle is that the viscous forces acting on a fluid particle moving along a streamline can be ignored, and so Eqn. 2 is only valid for fast moving flows where viscous forces are minimal. A classic example from biology where Bernoulli's principle applies is the construction of prairie dog burrows.

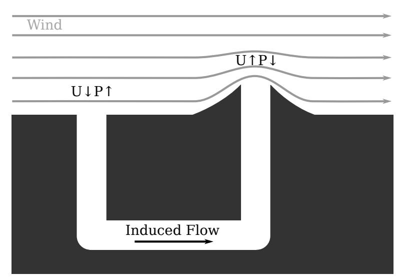


Figure 2: Induced flow in prairie dog burrows.

The underground tunnels in which these animals live are constantly supplied with fresh air via induced air flow, which relies on a pressure difference between the ends of the burrow to drive air flow through the tunnels. This pressure difference is achieved, as we will see in this lab, by the physical structure of the burrow and how this physical structure affects the nature of the air flow moving across the entrances to the burrow.

## *Lift forces*

Drag and lift forces arise when there is fluid motion relative to a surface. As we noted in class, drag follows from two types of stresses: viscous (shear) stresses and pressure (inertial) stresses. Together those stresses constitute the total downstream force faced by an object moving relative to a fluid. Lift forces arise from an asymmetric pressure distribution about an object and is, for our purposes here, defined as a force *perpendicular* to the direction of fluid motion. According to the principal of continuity (conservation of mass), we suggested that the flow over the top of a wing is faster than that beneath the wing. And, according to Bernoulli's principle that faster flow is associated with a lower pressure above the wing than beneath the wing. That pressure difference is one way to understand how lift is generated by an asymmetric objet in flow.

Predicting lift and drag forces on objects with complex shapes immersed in fluids in which both density ($\rho$) and viscosity ($\mu$) are critical determinants of the flow is challenging and, in fact, there are no analytic solutions to those forces. We turn instead to direct measurements of lift ($L$) and drag ($D$) and their coefficients $C_L$ and $C_D$ respectively:

$$C_D = \frac{2D}{\rho S U^2} \tag{3}$$

$$C_L = \frac{2L}{\rho S U^2} \tag{4}$$

where $U$ is the velocity of the fluid and $S$ is the surface area of the object. For objects like spheres, that surface area is the projected area of the sphere ($\pi r^2$). For wings $S$ is the planform area, which is the area of the wing as you look down on it. In this lab, we will explore how the lift force and its coefficient vary with the shape of a wing, it's angle of attack and the wind speed.

Both lift and drag coefficients depend upon the Reynolds number ($Re$) of an object, the shape of the object (including its orientation in the flow), and even its surface texture. Recall that the Reynolds number measures the relative importance of inertial to viscous stresses:

$$Re = \frac{\rho U L}{\mu} = \frac{UL}{\nu} \tag{5}$$

where $\nu$ is the kinematic viscosity of the fluid and $L$ is the characteristic length of an object. For spheres $L$ is their diameter, for wings it is their chord length.

As mentioned above, the lift and drag coefficients depend upon a host of parameters (e.g. $Re$ and shape). For wings in particular, the aspect ratio, camber, and angle of attack $\alpha$ all strongly affect the magnitude of the lift coefficient. The angle of attack is defined as the angle of the wing with respect to the oncoming air. As you will see in this lab, increasing the aspect ratio increases the lift and, sadly, the drag. For soaring and gliding animals it is helpful to hold the wings at an angle of attack that maximizes the lift for a given drag.

Thus a vulture operating its wing at an angle of attack that has the greatest lift for a given amount of drag, descends at the shallowest

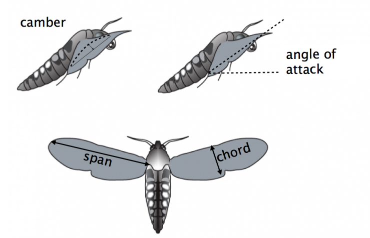


Figure 3: the span, chord length, angle of attack and camber of wings are shown for the most relevant study creature of all: the hawkmoth *Manduca sexta*

Figure 4: Aspect ratios for a variety of bird species adapted from Otto Lilienthals study of brids as inspiration for aircraft design

angle possible. Importantly, very steep angles of attack can lead to the formation of a significant wake behind the wing with massive drag forces and, sadly, stall: the complete loss of lift. In this lab, you will measure the relationship between lift and angle of attack for real wings. The aspect ratio ($AR$) of wings measures how long and thin they are. For a rectangular wing, that aspect ratio is simply the span of the wing ($b$) divided by the chord length ($c$). For wings with more irregular shape we commonly define the aspect ratio as:

$$AR = \frac{b^2}{S} \tag{6}$$

where $S$ is the surface (planform) area of the wing. You can verify that for rectangular wings the aspect ratio is merely the span divided by the chord.

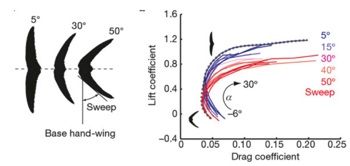


Figure 5: Each curved line above is called a wing polar where increasing the angle of attack increases the lift and drag coefficients in a swift wing. The lift and drag coefficients of swift wings depends on both the sweep angle of the wings (from 5 to 5 degrees) and the angle of attack (from -6 to 30 degrees). Lentink et al. *Nature 446, 1082-1085(26 April 2007)*

## *Burrowing into the measurements*

In this section of the lab, you will have two options: (1) you can build a physical model of a prairie dog burrow and (2) a computational model using a simulator on an iPad.

For option 1 you will be constructing models of prairie dog burrows using cardboard, plastic tubing, and clay. Construct a burrow as shown in Figure 2 above. In the tunnel you have made, add some water leaving the meniscus visible. We will be using the compressed air taps to provide a flow over the entrances to the burrow, and we will restrict the orientations of the entrances to being perpendicular to the direction of the flow.

Place your burrow 2 inches from the exit of the air nozzle and slowly open the valve to the compressed air. When air passes over the entrances to the model burrow, you will hopefully see the water column in the tubing shift position. How does the change in water column position relate to the pressure difference between the two entrances? How does the pressure difference depend on burrow shape, relative height of the entrances, and relative size of the entrance holes?

For option 2, you will launch WindTunnel Pro on the iPads provided. Use the following steps to create a simulation of the flow:

- Set the Parameters to default
- In the Interaction menu select Draw Wall
- Draw the geometry of interest
- In the interaciton menu select "draw smoke"

- In the Visualization menu select under the Physics sub-menu either Pressure or Speed
- Describe your results in the worksheet attached.

### *Measuring Lift*

In this section of the lab, you will explore how both wing shape and angle of attack influences the lift generated by real wings. You will be equipped with a wing holder and materials for creating wings. The wing holder mounts to a fixture that supports the wing and attaches to a very sensitive pan balance. The pan balance, in return, provides a direct measure of the change in vertical force. Note that the balance reports grams (which is not force – but a mass) so you will have to convert to Newtons.

The wing mounting fixture has holes spaced every 15 degrees, from horizontal (0 degrees) to vertical (90 degrees). You can simply rotate your wing for each angle and record the value on the pan balance. What angles of attack were most effective in generating lift?

If time permits, you can also draw a wing using the Wind Tunnel app on the iPads. There you can actually estimate the lift generated by sections of interest. This, however, is just a two dimensional simulation.

### *Exploring wings*

Finally, experiment with constructing your own (bio-inspired or otherwise) wings and exploring their lift characteristics as a function of shape using your wind tunnel and calibrated force transducer. You will probably find adjustments of wing camber and aspect ratio to be most interesting here, but feel free to explore other shape parameters!

Figure 6: Wings inspired technology

# Lab 6: Lift and Bernoulli

*Note:* Hand in one worksheet per lab group
Lab Section: ________________________
Name 1: ________________________ Name 2: ________________________

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## Prairie dog burrow

Draw a diagram of your model below.

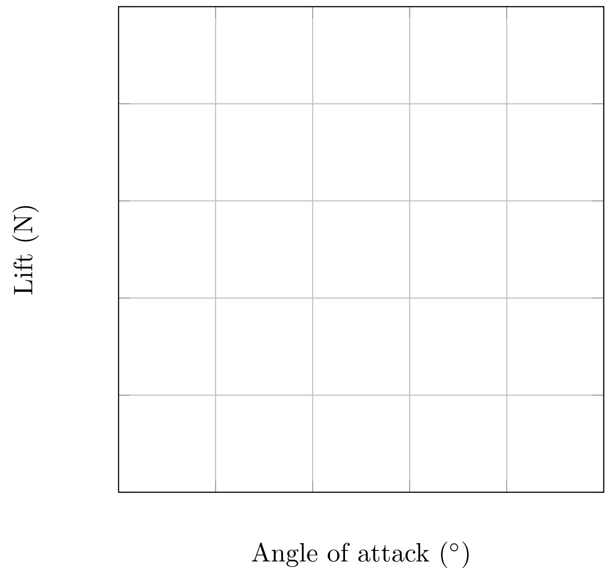
What was the maximum pressure difference between the entrances of the burrow that you were able to achieve? (The pressure difference is

Given that pressure difference, what is your predicted velocity difference? (you will want to use Bernoulli's
How did the shape of the entrance mounds affect your pressure difference?

How about the size of the burrow entrances?

How would you expect these parameters to affect the pressure differential, based on Bernoulli's equation?

## Lift on a wing




What angle of attack provided the highest lift from the wing?

## Making wings

How did the performance of your constructed wing vary with aspect ratio and camber?

Choose one additional shape parameter and test how varying this shape parameter affects the lift generated by your wing. Describe your results below.