Function of an anemometer:
- Measure some or all of the components of the wind vector
- In homogeneous terrain, vertical component is small → express wind as 2-D horizontal vector
- For some applications, vertical component is very important!

Orthogonal wind components
- u-component
  - Positive to the east (i.e., westerly winds)
- v-component
  - Positive to the north (i.e., southerly winds)
- w-component
  - Positive upward

Another way to report the wind:
- Speed and direction
  - Direction is measured in degrees clockwise from north
- Elevation angle

Ideal sensor:
- Responds to the slightest breeze, but withstands hurricane- or tornado-force winds
- Responds rapidly to turbulent fluctuations
- Linear output
- Simple dynamic performance characteristics

In reality:
- A sensor cannot respond to low wind speeds and survive strong winds
- You must select a sensor that meets your particular needs
Wind Force

- Many anemometers respond to the drag force of the wind on an object:

\[ T = \frac{1}{2} C_d \rho A r \left(V - s\right)^2 \]

where
- \(C_d\) = drag coefficient (dimensionless; a function of shape and wind speed)
- \(\rho\) = air density (kg m\(^{-3}\))
- \(A\) = cross-sectional area of the sensor (m\(^2\))
- \(V\) = wind speed (m s\(^{-1}\))

Cup Anemometer

- Consider the torque on a single cup:

\[ T = \frac{1}{2} C_d \rho A r \left(V - s\right)^2 \]

Let the cup move at tangential speed \(s\) in the same direction as the wind:

Why do the cups spin at all?

- If the rotational velocity of the system is in equilibrium with the airflow, then the torque on each cup must be equal:

\[ T_1 = \frac{1}{2} C_1 \rho A r (V - s)^2 \]
\[ T_2 = \frac{1}{2} C_2 \rho A r (V + s)^2 \]

- If the cups do not spin in a non-zero wind, then \(s = 0\) and \(C_1\) must be equal to \(C_2\).
- Obviously, this is an undesirable result!

Why do the cups spin at all?

- Since we want the cups to spin in the wind, the design of the cups must allow for \(C_1 > C_2\)
- The difference in drag coefficients allows the cups to spin
- The drag coefficient is larger for the open cups than for the closed cups
- A three-cup anemometer provides the best torque for measuring wind speed

Tangential velocity of the cups

- We can solve for the tangential velocity of the two-cup system, given the wind velocity:

\[ s = V \left[ \frac{C_1 + C_2 - 2\sqrt{C_1 C_2}}{C_1 - C_2} \right] \]

- The tangential velocity of the cups is a function of only the wind velocity and the drag coefficients
- Calibration of the system does not depend upon the density of the air
- Ideally, the cup system has a linear response
- The same principles apply to a three-cup system
Starting and Stopping Thresholds

- The cups will not spin until the force of the wind overcomes the starting friction of the bearings.
- Friction stops the cups at very low wind speeds.
- These thresholds differ because running friction is much less than static friction.

Starting Threshold is typically ~0.5 m s\(^{-1}\) for a three-cup and ~1 m s\(^{-1}\) for a propeller.

Improving the Starting Threshold

- To decrease the starting threshold:
  - Decrease the starting friction of the bearings
  - Increase the torque: \(T = \frac{1}{2} C_r M V^2\)
- To increase the torque:
  - Increase the torque arm length (r)
  - Make the cups larger (A)
- But recall that these sensors must survive strong winds:
  - Increase mass
  - Decrease torque arm length
  - Decrease area of cups
- We have a serious design tradeoff!

Sensor Output for Cup or Propeller Anemometers

- Raw output
  - Mechanical rotation rate of the cup wheel and supporting shaft
  - Shaft is coupled to an electrical transducer that produces an electrical output signal
    - DC voltage signal proportional to shaft rotation rate
    - AC voltage signal with frequency proportional to shaft rotation rate
- Another option: Optical transducer
  - Measures pulses when the rotating wheel interrupts a beam of light

Cosine Response: A Static Error

- Ideally, the output follows a cosine curve if the wind speed is kept constant, but the direction is turned off-axis.
- In reality, most cup anemometers overestimate and propeller anemometers underestimate \(V_h\).

\[
V_h = |V| \cos \theta
\]

Where \(\theta\) is the angle between the wind vector and the horizontal plane.

Cosine Response: A Static Error

- Beaded edges and flat surfaces can reduce the cosine error.
Dynamic Performance

- Recall: 
  \[
  \tau \frac{dV}{dt} + V = V_i 
  \]

- Where:
  - \( V \) is the measured wind speed (m s\(^{-1} \))
  - \( V_i \) is the actual wind speed (m s\(^{-1} \))
  - \( I \) is the cup wheel moment of inertia (kg m\(^2\))
  - \( R \) is the cup wheel radius (m)
  - \( \rho \) is the air density
  - \( A \) is the cross-sectional cup area
  - \( C \) is a constant (related to \( C_d \))

- For a given anemometer, we cannot specify \( \tau \), since it varies with wind speed!
- The distance constant, \( \lambda \), is the dynamic specification for anemometers (not \( \tau \))
- To minimize the distance constant, reduce \( m_c \) and increase \( A \)
  - Is it always practical to do this?
  - The length of the radius arm is irrelevant

Over-Speeding: A Dynamic Error

- Our equation is now tough to solve and is non-linear because \( \tau \) is a function of \( V_i \)
  \[
  \tau = \frac{\lambda}{V_i} 
  \]
- When \( V_i \) is low, \( \tau \) is high and when \( V_i \) is high, \( \tau \) is low
  - The anemometer responds more rapidly to an increasing step change than to a decreasing step change

Pitot-Static Tube

- Measures dynamic and static pressures:
  - At the stagnation port:
  - At the static ports:
Hot-Wire and Hot-Film Anemometers

- Use heat dissipation:
  - Wind flow cools a heated wire
  - The wire is heated to a particular temperature through current flow
  - The temperature is held constant by adjusting the current to balance the heat loss
  - King’s law describes the required current:
    \[ I^2 = A + B\sqrt{V} \]
    - A and B are empirical constants

- Response depends on thermal mass (heat capacity)
  - Use very fine platinum wires with \( d \sim 5 \mu m \)

- Very fast response
  - Well-suited for turbulence studies and aircraft measurements

- Drawbacks
  - Expensive and power-hungry
  - Susceptible to drift
  - Rain affects the measurements
    - Water causes cooling, which results in unrealistically high wind speed measurements

Static Sensitivity of Pitot-Static and Hot-Film Anemometers
Sonic Anemometer

- Measures the time required to transmit an acoustic signal across a fixed path
- Determines wind velocity along path
- We can also measure the virtual temperature!

Consider the wind blowing along the axis between a sound transmitter and a sound receiver:

\[ t_1 = \frac{d}{c + V_d} \]

Where

- \( t_1 \) = time for pulse to travel from Tx to Rx
- \( d \) = distance between Tx and Rx
- \( c \) = speed of sound
- \( V_d \) = wind speed along \( d \)

Switch the roles of the Tx/Rx pair to obtain \( t_2 \):

\[ t_2 = \frac{d}{c - V_d} \]

Calculate the velocity component parallel to the path (i.e., solve for \( V_d \)):

\[ V_d = \frac{d}{2} \left( \frac{1}{t_1} - \frac{1}{t_2} \right) \]

Consider the following measurements:

- \( t_1 = 591.5 \mu s \)
- \( t_2 = 574.5 \mu s \)
- \( d = 20 \text{ cm} \)

What is the velocity component parallel to the acoustic path?*

*Note that the wind typically blows at an angle that is off axis.

Sonic Anemometer: Example

We must measure time in microseconds

Sonic anemometer response is on the order of 10 Hz

To get three-dimensional winds, we need three sonic transmitter/receiver pairs
Why place the anemometer at 10 m?

The logarithmic velocity profile (a.k.a. log wind profile) describes the vertical distribution of horizontal winds in the surface boundary layer:

- \( \frac{u}{u_*} = \frac{\ln(z/d)}{\kappa} \)
- \( u_* \) is the friction velocity (m s\(^{-1}\))
- \( \kappa \) is von Kármán’s constant (≈0.41)
- \( d \) is the mean height of the vegetation (zero plane displacement)
- \( z_0 \) is the roughness length (a function of surface characteristics)
- \( \psi \) is a stability term
- \( L \) is the Monin-Obukhov stability parameter

Consider the logarithmic wind profile of the surface layer (first 10 meters):

- The wind profile above 10 m changes little with height and the surface layer logarithmic profile no longer applies
- Above the surface layer, the balance between PGF, Coriolis, and turbulent drag applies, giving us the Ekman layer