Anemometry

Anemometry

- 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!

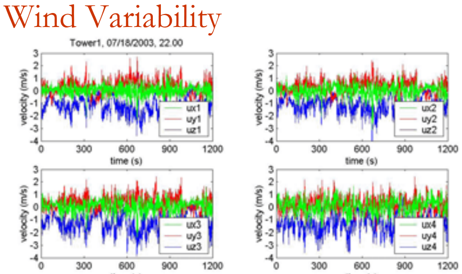
Anemometry

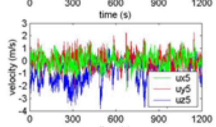
- Orthogonal wind components
  - *u*-component
    - Positive to the east (i.e., westerly winds)
  - *v*-component
    - Positive to the north (i.e., southerly winds)
  - *w*-component
    - Positive upward
- Another way to report the wind:
  - Speed and direction
    - Direction is measured in degrees clockwise from north
  - Elevation angle

Wind Conventions and Characteristics

- Standard units
  - meters per second (m s^{-1})
  - nautical miles per hour (knots; kts)
- Flow in the atmospheric boundary layer is turbulent → wind vector varies
- We describe the mean wind over a time period
  - WMO specifies 10 minutes
  - Gusts (deviations from the mean, e.g., 1-min gusts)
  - Turbulence intensity ($\sigma_V / \bar{V}$)

Wind Variability





Results from the sonic measurements in downtown Oklahoma City during the field campaign Joint Urban 2003, July 2003

Source: Petra Klein

Anemometry

- 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

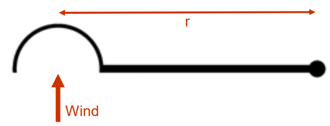
Wind Force

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

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

Cup Anemometer

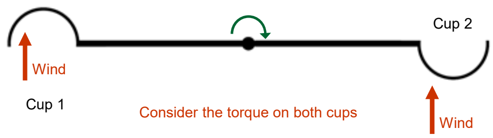
- Consider the torque on a single cup:



- Let the cup move at tangential speed *s* in the same direction as the wind:

Cup Anemometer

- Add a cup on the other side:



$$T_1 = \frac{1}{2} C_1 \rho A r (V - s)^2$$

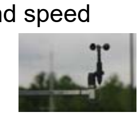
$$T_2 = \frac{1}{2} C_2 \rho A r (V + s)^2$$

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:
- If the cups do <u>not</u> 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

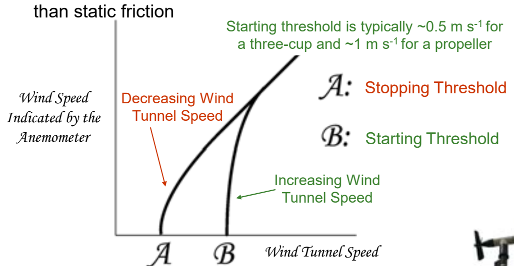
- We can solve for the tangential velocity of the two-cup system, given the wind velocity:

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

  - 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



Improving the Starting Threshold

- To decrease the starting threshold:
  - Decrease the starting friction of the bearings
  - Increase the torque: $T = \frac{1}{2} C_d \rho A r V^2$
- 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

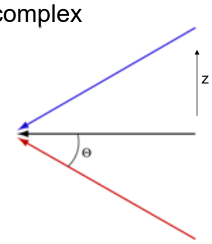
- Raw output
  - Mechanical rotation rate of the cup wheel and supporting shaft
- Shaft is coupled to an electrical transducer that produces an electrical output signal
  - DC voltage signal proportional to shaft rotation rate
  - AC voltage signal with frequency proportional to shaft rotation rate
-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

Cosine Response: A Static Error

- Cup and propeller anemometers measure V_h
- Wind may have a vertical component in turbulent flow or around complex terrain/buildings
- Each of these 3 vectors would give the same V_h:
- Ideally,

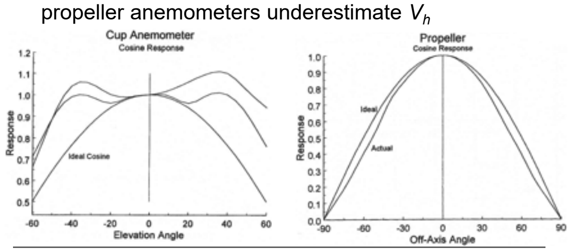
$$V_h = |\vec{V}| \cos\theta$$

  - θ is the angle between the wind vector and the horizontal plane



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



Cosine Response: A Static Error

- Beaded edges and flat surfaces can reduce the cosine error

Source: http://imdpune.gov.in/surface_instruments/workshop/Instruments/cupcounter.html

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)
  - ρ is the air density
  - A is the cross-sectional cup area
  - C is a constant (related to C_d)

Dynamic Performance

Dynamic Performance

- For a given anemometer, we cannot specify τ, since it varies with wind speed!
- The distance constant, λ, is the dynamic specification for anemometers (not τ)
- 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

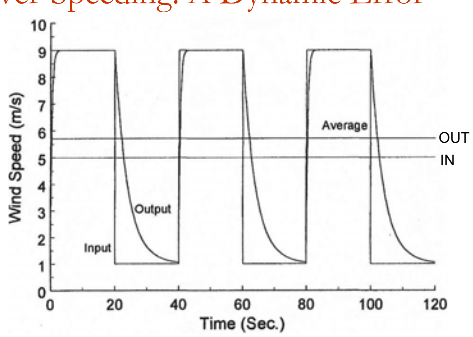
Over-Speeding: A Dynamic Error

- Our equation is now tough to solve and is non-linear because τ is a function of V_i

$$\tau = \lambda / V_i$$

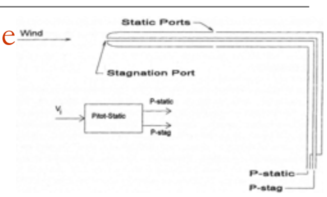
- When V_i is low, τ is high and when V_i is high, τ is low
  - The anemometer responds more rapidly to an increasing step change than to a decreasing step change

Over-Speeding: A Dynamic Error



The average *measured* wind speed is larger than the average *true* wind speed

Pitot-Static Tube



- Measures dynamic and static pressures:
  - At the stagnation port:
  - At the static ports:

Pitot-Static Tube

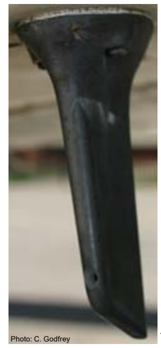
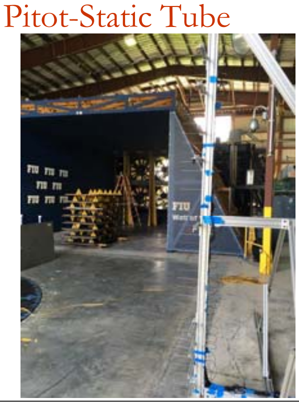


Photo: C. Godfrey

Photo: J. Siegel

Underside of an airplane wing, facing forward

Pitot-Static Tube



Photos: C. Godfrey

Hot-Wire and Hot-Film Anemometers

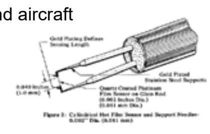
- Use heat dissipation:
  - Wind flow cools a heated wire
  - The wire is heated to a particular temperature through current flow
  - The temperature is held constant by adjusting the current to balance the heat loss
  - King's law describes the required current:

$$I^2 = A + B\sqrt{V}$$

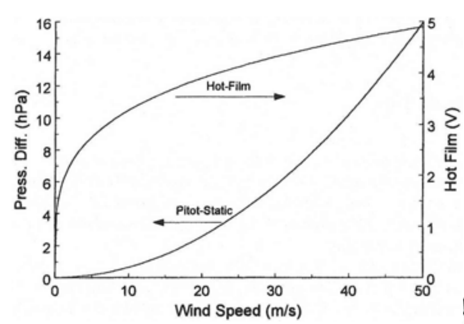
    - A and B are empirical constants

Hot-Wire and Hot-Film Anemometers

- Response depends on thermal mass (heat capacity)
  - Use very fine platinum wires with d ~ 5 μm
- 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

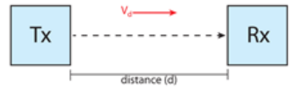


Sonic Anemometer

- 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!

Sonic Anemometer

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

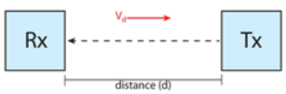


$$t_1 = \frac{d}{c + V_d}$$

- 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

Sonic Anemometer

- 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):

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

Sonic Anemometer: Example

- Consider the following measurements:
  - t_1 = 591.5 μs
  - t_2 = 574.5 μs
  - d = 20 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

- Consider the following measurements:
  - t_1 = 591.5 μs
  - t_2 = 574.5 μs
  - d = 20 cm
- What is the virtual temperature?

Sonic Anemometer

- 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:
  - Where
    - u_* is the friction velocity (m s^{-1})
    - κ is von Kármán's constant (≈0.40)
    - d is the mean height of the vegetation (zero plane displacement)
    - z_0 is the roughness length (a function of surface characteristics)
    - ψ is a stability term
    - L is the Monin-Obukhov stability parameter

Why place the anemometer at 10 m?

- 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