Wind Turbines for use in Cities and Suburbs: Basic Wind Physics

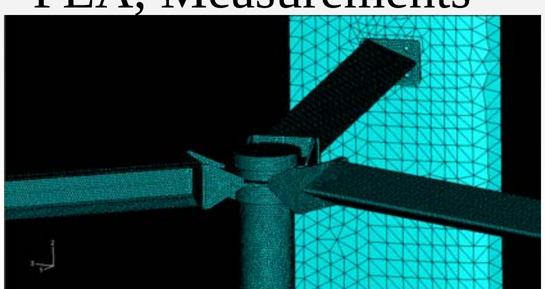
Stephen Tullis

Small wind turbines in the urban environment: Current Research at McMaster University

Nominal performance:
Full-scale wind tunnel testing

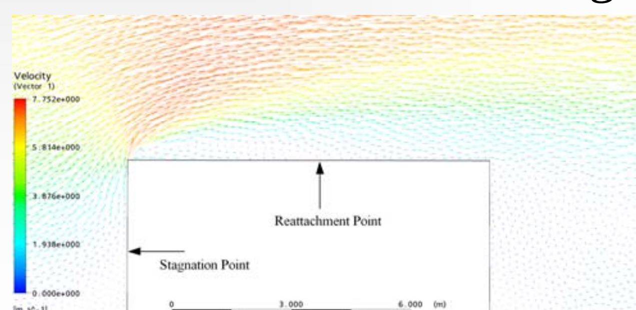
Actual performance:
Rooftop testing

Structural and vibrations:
FEA, Measurements



Kevin McLaren

CFD Analysis:Flow within turbine and around building



Stephen Kooiman

Background

- Two types of wind turbines according to shaft orientation:
  - Horizontal axis wind turbine (Most common, well known)
  - Vertical axis wind turbine (VAWT):
    - Drag type (Cup anemometers, Savonius rotors)
    - Lift type (Darrieus turbines and Variations)

Power

- Basic physics - instantaneous power P

$$P = c_p \frac{1}{2} \rho v_{wind}^3 A$$

c_p	power coefficient $=$ turbine efficiency ranges $0 \rightarrow 0.59$
ρ	air density
v_{wind}	windspeed
A	turbine area

Power - add units

- Basic physics - instantaneous power P (W)

$$P = c_p \frac{1}{2} \rho v_{wind}^3 A$$

c_p power coefficient = turbine efficiency ranges $0 \rightarrow 0.59$

ρ air density (kg/m^3)

v_{wind} windspeed (m/s)

A turbine area (m^2)

eg 10m diameter horizontal turbine with a c_p of 0.4 in 12 m/s wind

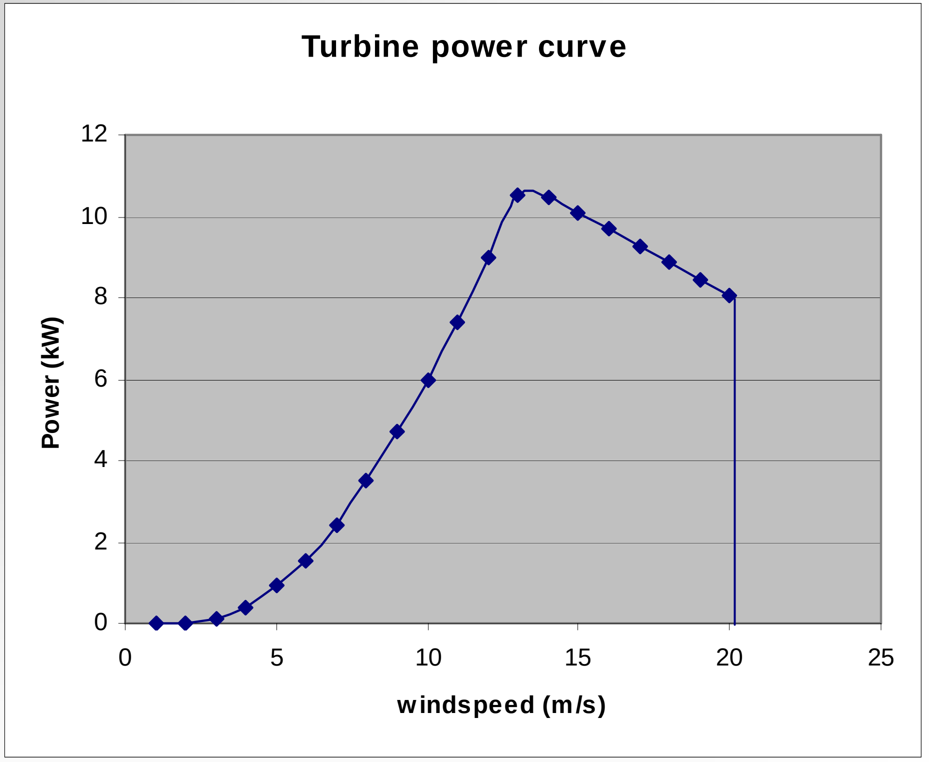
$$P = c_p \frac{1}{2} \rho v_{wind}^3 A = (0.4)\frac{1}{2}(1.2)(12)^3 \left(\frac{\pi 10^2}{4} \right) = 32570W = 32.6kW$$

Power Curve

- Plot of power
  as function of windspeed

- includes area *A*
- includes efficiency c_p
- note $P \propto v^3$
- cut-out / cut-in
- not entirely reliable

- RATED POWER



Turbine efficiency (c_p)

- Small wind efficiencies are lower than large turbines
  - c_p ~ 0.2 - 0.35
  - charlatan c_p 0 - 0.1 or claim >0.59
  - is often function of windspeed

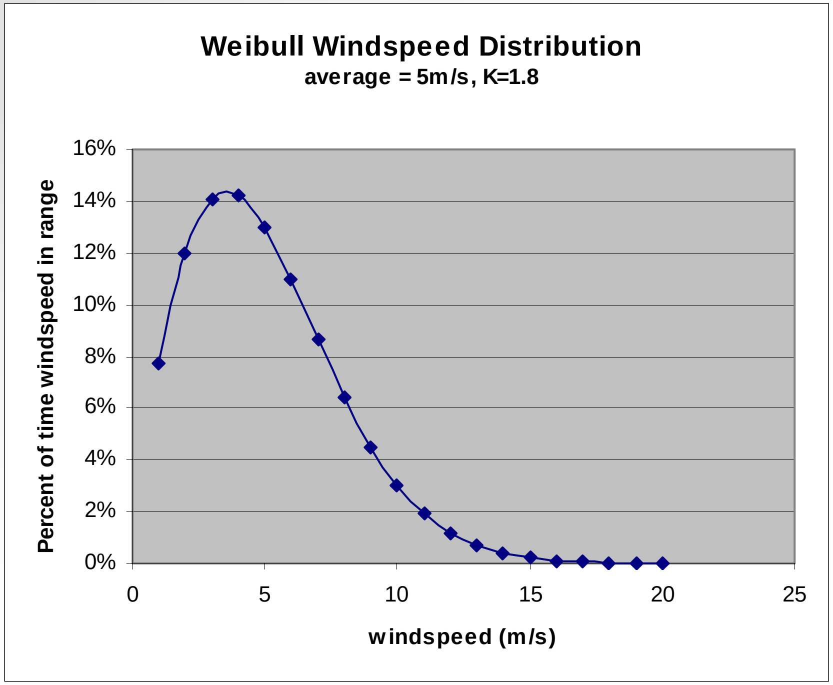
- Dirty air of cities (turbulence, unsteadiness) c_p reduced
  - inherently
  - ability of controller to respond

Average power output

- Depends on turbine power curve
  - what turbine can produce in given windspeeds

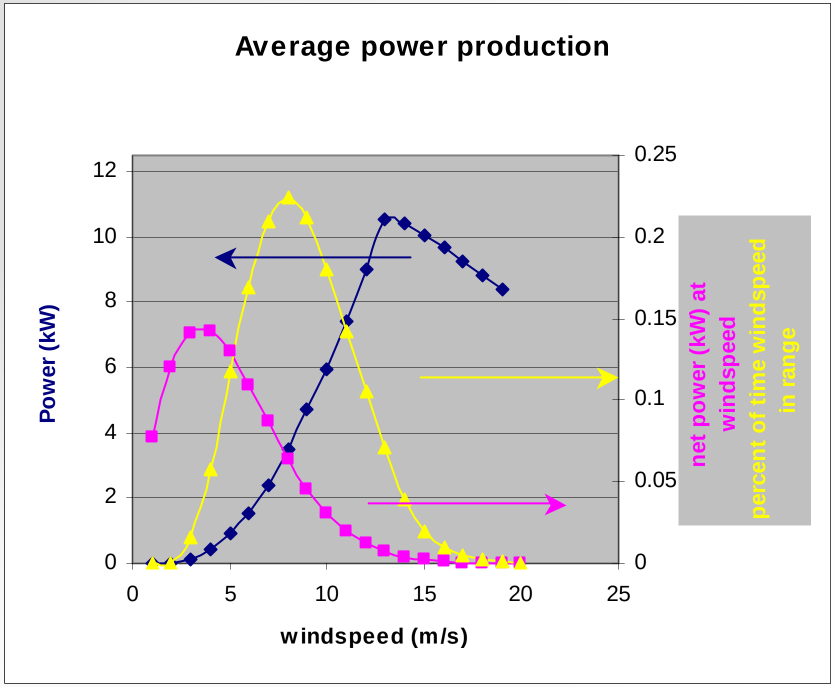
- Also wind distribution
  - how windspeed varies throughout the year
  - Weibull distribution is a common fit to measured data

  - note: due to v_{wind}^3 , you **cannot** just use average windspeed



Average power output

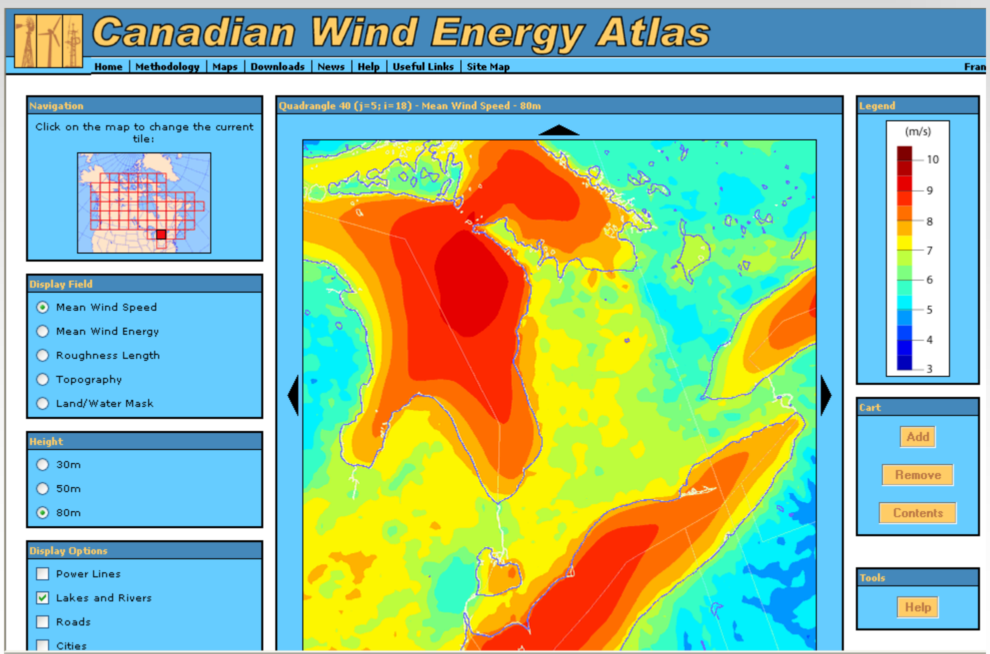
- Multiply turbine power curve and windspeed distribution and add up for average power output

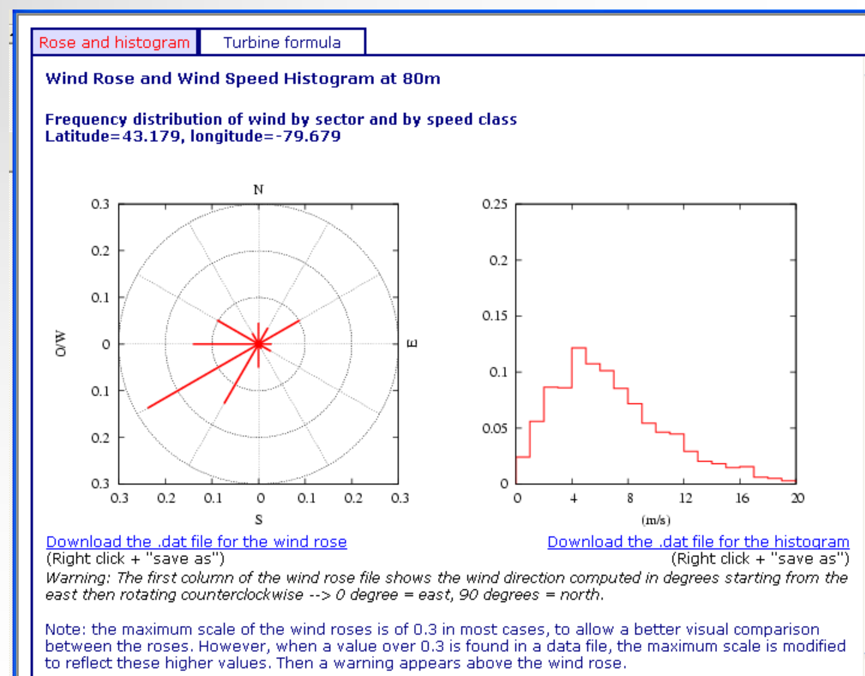


- Multiply this by time under consideration for total power production (eg average power output × 24 h/day × 365days/year = annual power supply in kW-h)
  - so average of 1kW production gives 8760 kW-h in a year

Wind Data

- Canadian Wind Atlas (www.windatlas.ca)
  - average windspeed, wind distribution at various heights



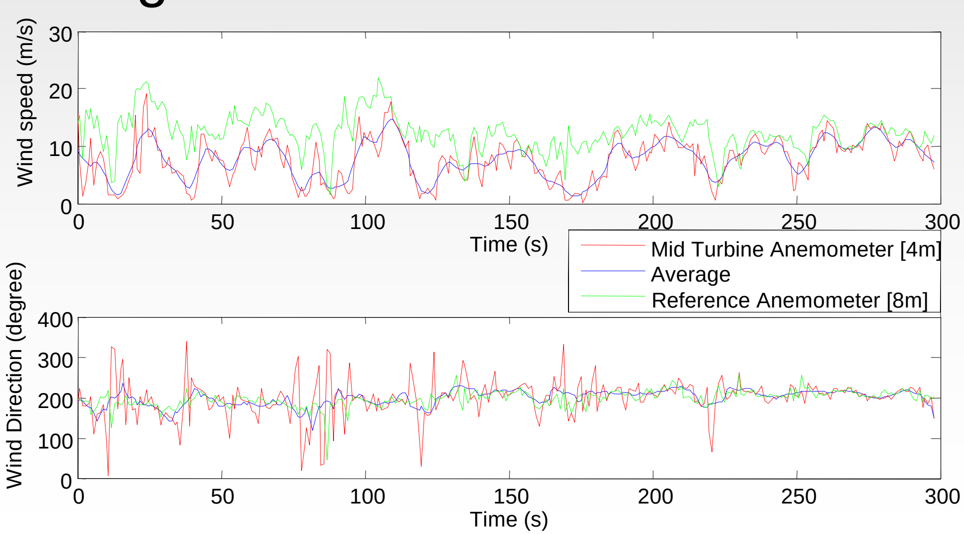


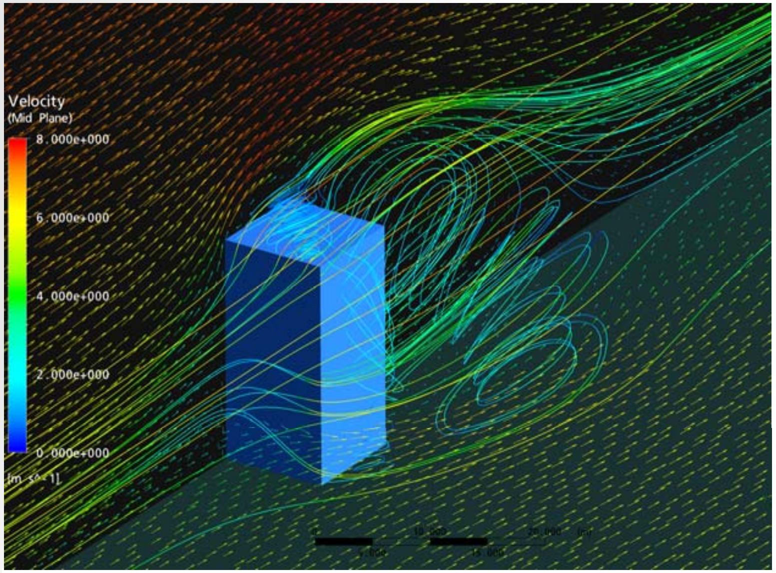
Urban wind

- Lower wind velocity due to larger ground roughness within urban environments

- Complex vortical flow structures over and around buildings

- High turbulence levels





Numerical Modelling of a Building with Normal Flow to the Building’s Face

Wind data (Urban)

- Urban installation is very location sensitive
  - hills, escarpments, trees, buildings

- Rough rules of thumb
  - clear of obstacles
  - higher is better
  - measure?

- Urban wind is unsteady and turbulent
  - affects (reduces) c_p of turbines

Noise

- Noise is proportional to the fifth power of blade velocity
  - in horizontal turbines the fastest bit of the blades are the tips
  - practically all noise generated by tips
  - increase of 50% in tipspeed increases noise by a factor of $(1.5)^5$ ~ 8
- Variable between manufacturers
  - other factors: trailing edge sharpness, flutter

Vibration

- All structures (turbines, towers, buildings) have natural frequencies at which they want to vibrate
- Turbines vibrate
  - unbalanced rotation   (1 per RPM)
  - uneven aerodynamic loads on blades eg tower pass, wind shear (3 per RPM)

- Most important that frequency of excitation does not co-incide with any natural frequency

Betz Limit

Mass flow $\dot{m} = \rho c_2 A_2$

Power to disk $P = {W}/{t} = \dot{m} c_2 \Delta c$

Energy lost by wind $P = \frac{1}{2}\dot{m} c_1^2 - \frac{1}{2}\dot{m} c_3^2 \quad \Rightarrow c_2 = \frac{1}{2}(c_1 + c_3)$

Plug in $P = \frac{1}{2}\rho c_2 A_2 c_1^2 - \frac{1}{2}\rho c_2 A_2 (2c_2 - c_1)^2$

and define $c_P \equiv \dfrac{P}{1/2\,\rho A_2 c_1^3} = \dfrac{1/2\,\rho A_2 c_2\left[c_1^2 - (2c_2 - c_1)^2\right]}{1/2\,\rho A_2 c_1^3} = \dfrac{4\left[c_2^3 - c_1 c_2^2\right]}{c_1^3}$

Find $c_{P\max}$ by taking $\dfrac{dc_P}{dc_2} = \dfrac{4}{c_1^3}\left[3c_2^2 - 2c_1 c_2\right] = 0 \quad \Rightarrow c_2 = \dfrac{2}{3}c_1$

$$\Rightarrow c_{P\max} = \frac{16}{27} = 0.593$$

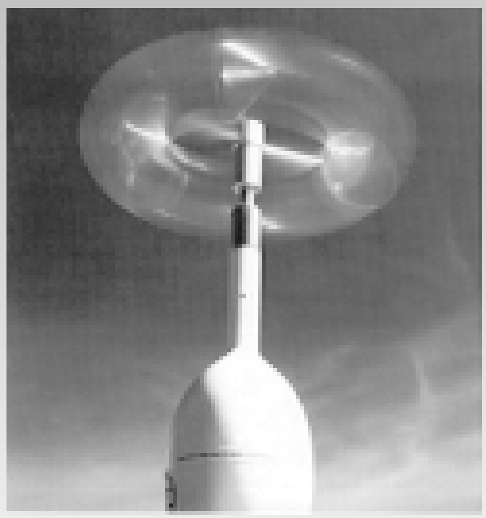
HAWT

Enercon Wind Parc at Calenzana in Corsica
Source: Wikipedia

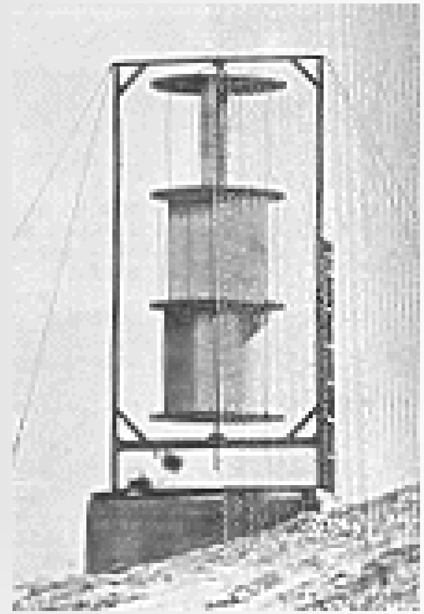
Bergey Excel (10kW)

Back

Drag type VAWT



Cup anemometer



Source: AWEA website

Savonius stacked rotor

- rugged
- (very) low efficiencies

Back

Back

Lift type VAWT

Sandia 34 m testbed
Darrieus “eggbeater”
Source: Sandia National Labs

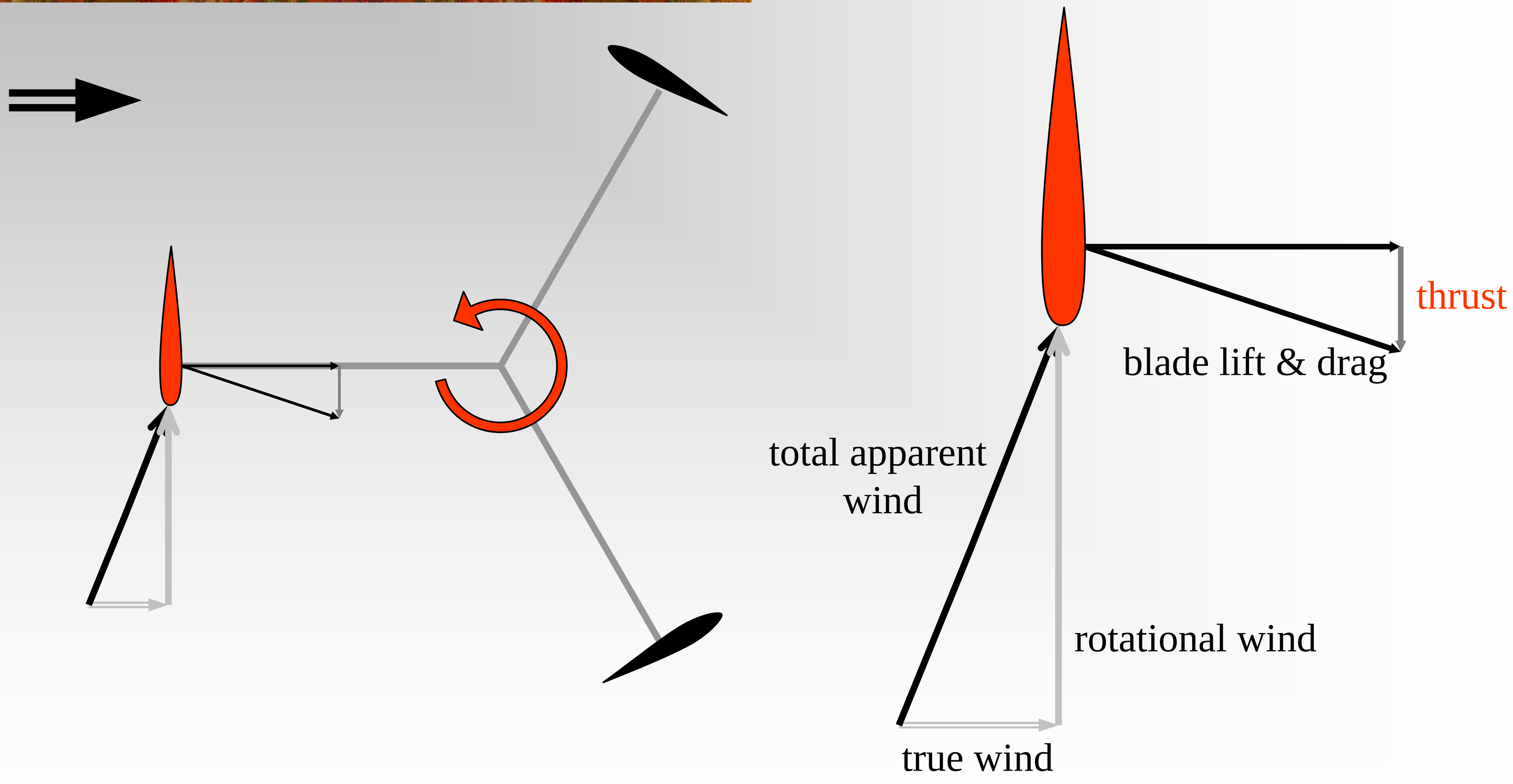
QR5
Source: Quiet Revolution

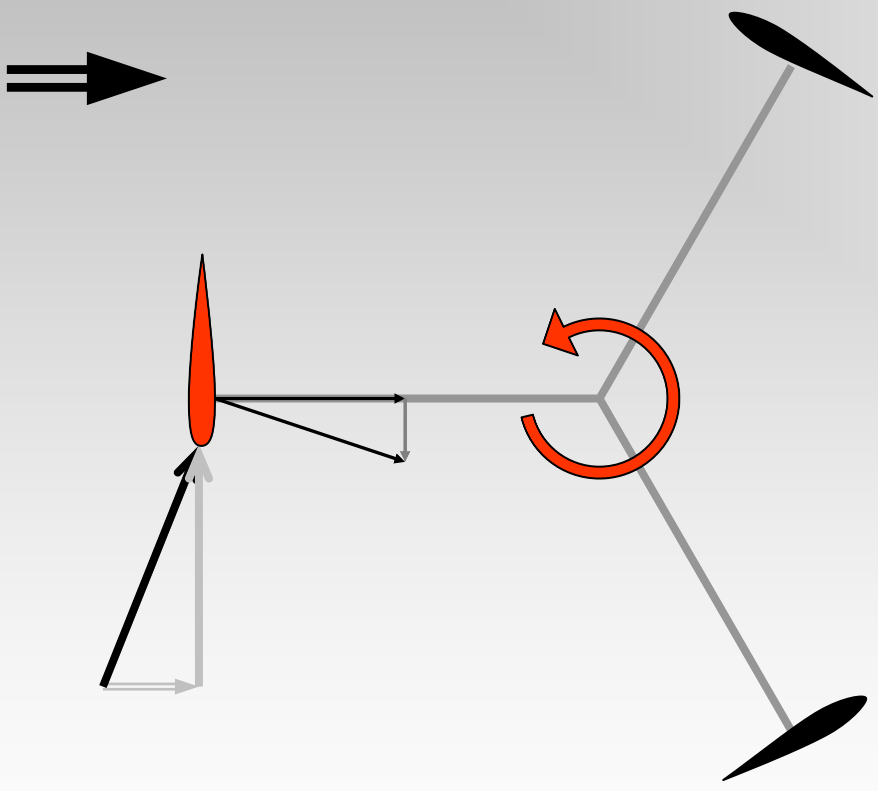
Cleanfield 2.5 kW

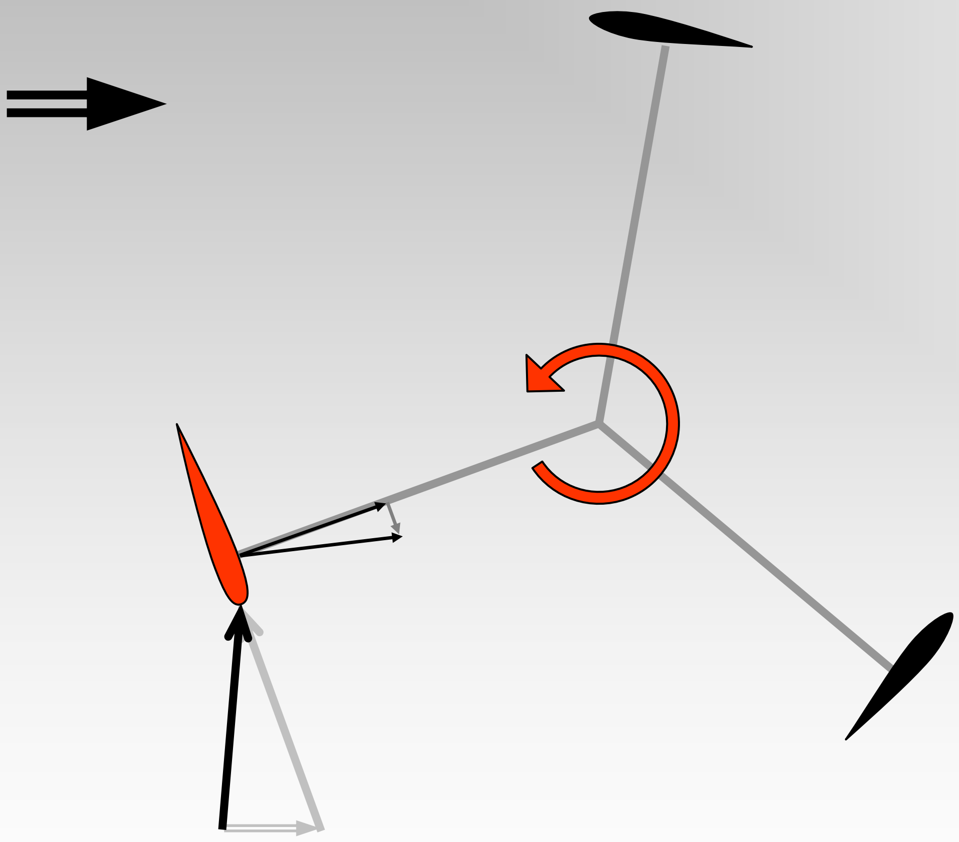
Vertical Axis Wind Turbines

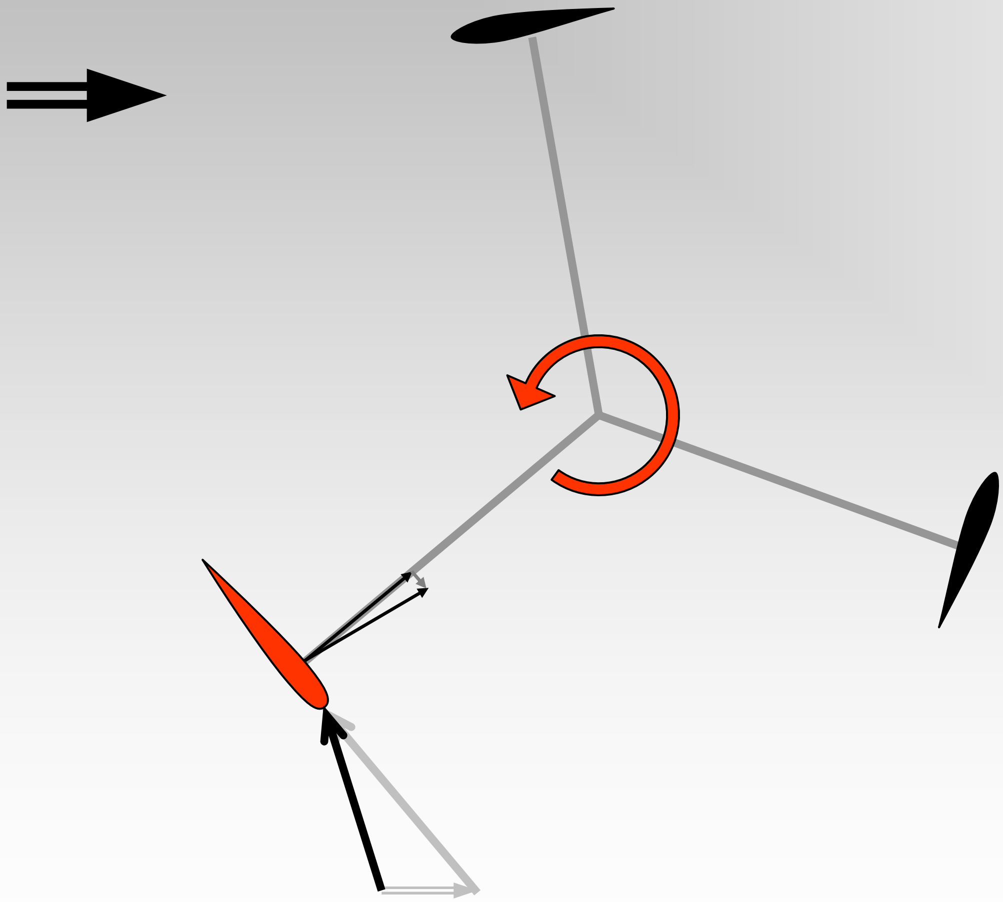
- Blades held by struts rotate about a vertical axis
- Blades move into, across, with and across the wind direction on each rotation
- Thrust depends on the *apparent wind* seen by the *rotating* blades

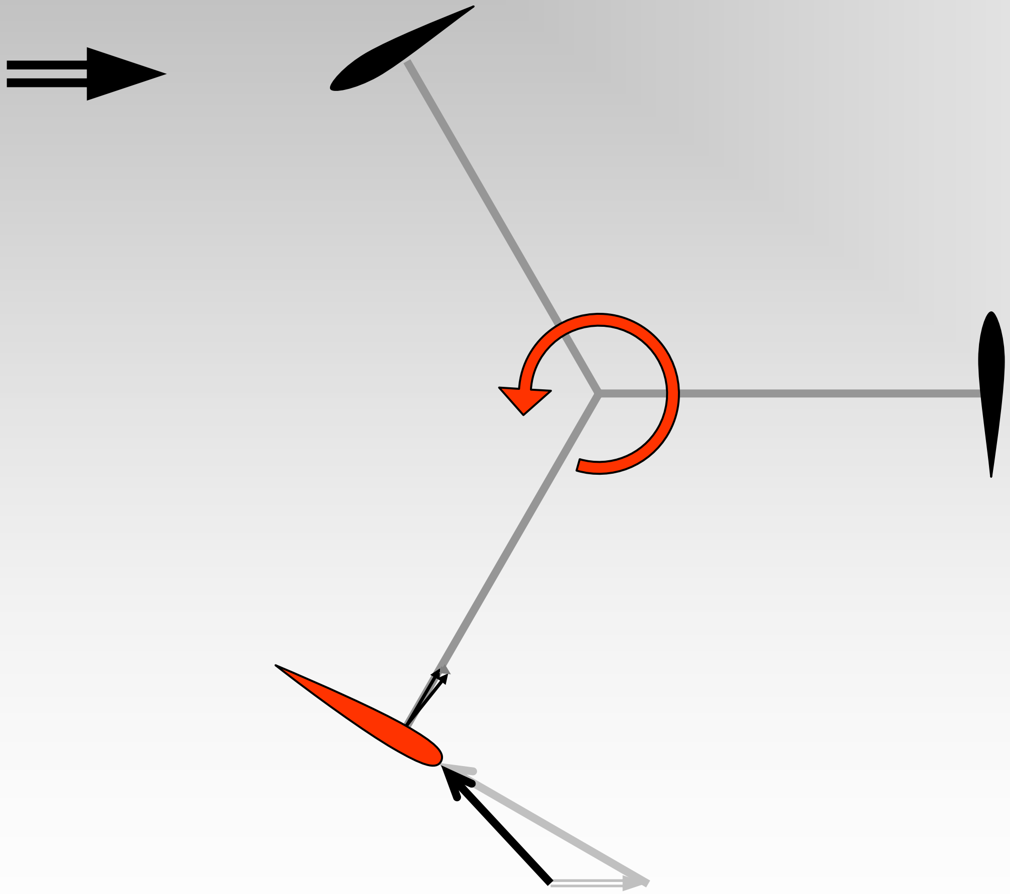
Basic Aerodynamics of VAWTs

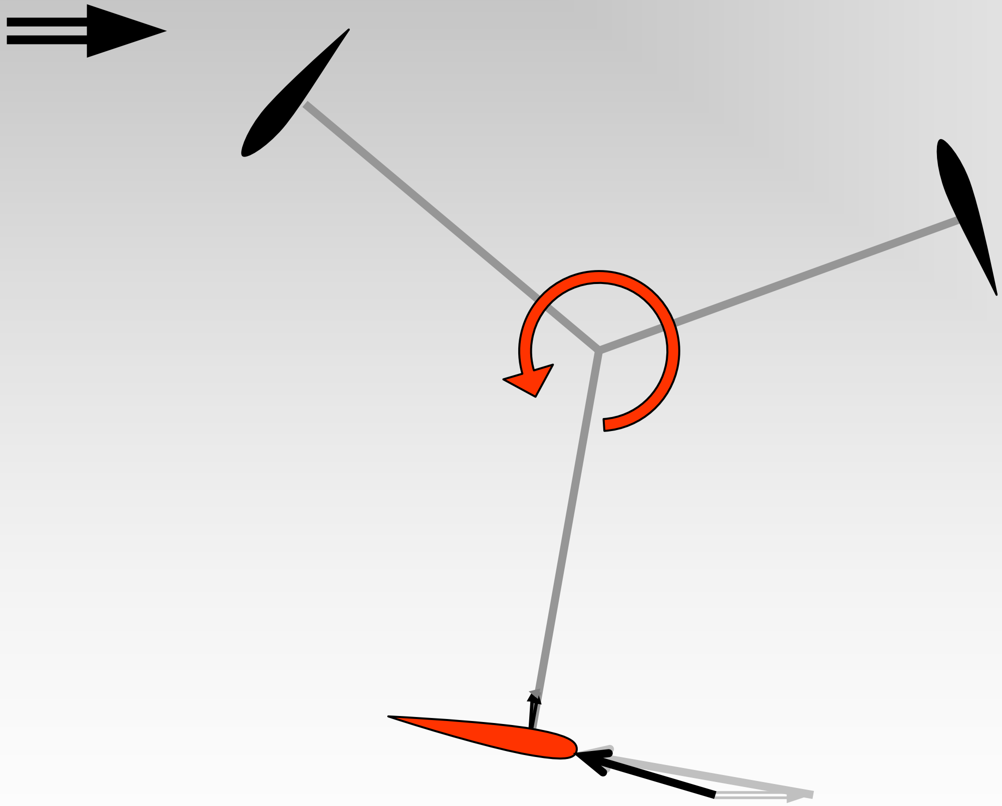


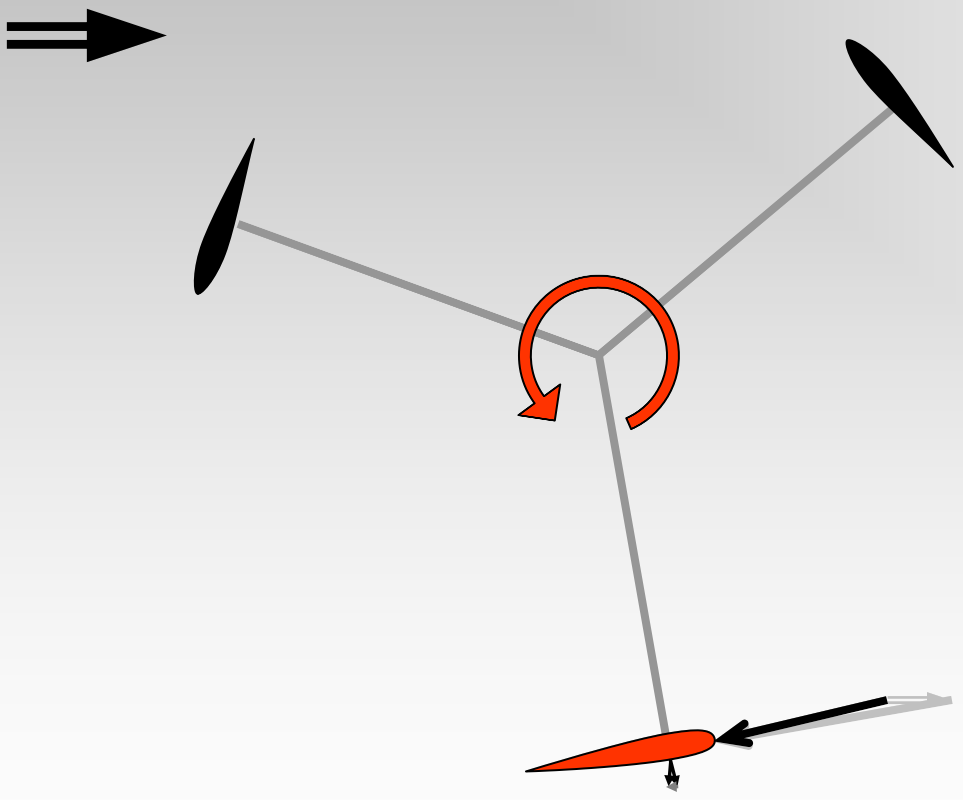


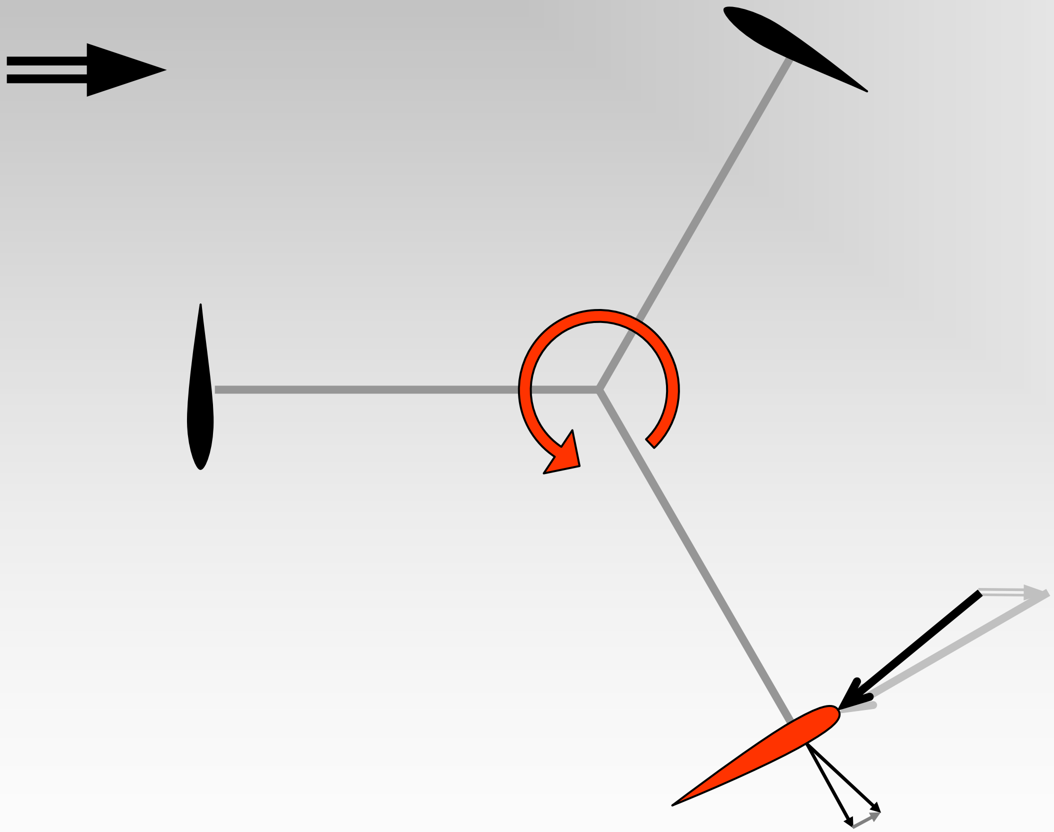


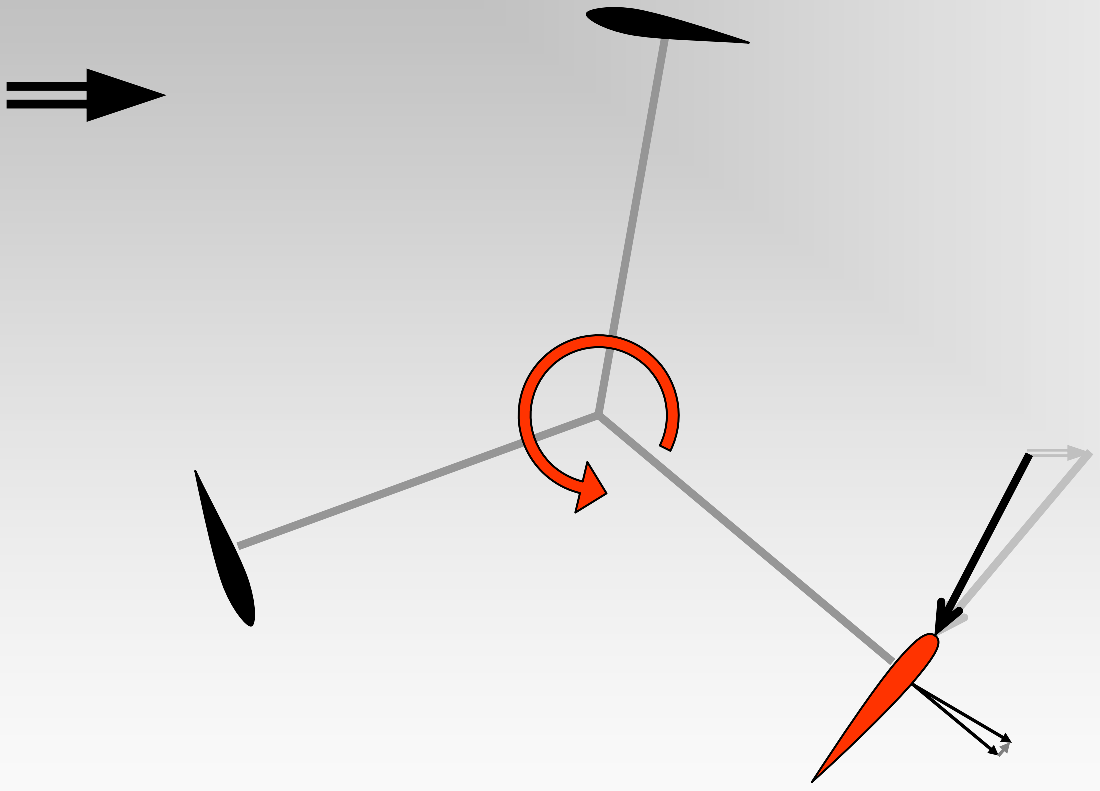


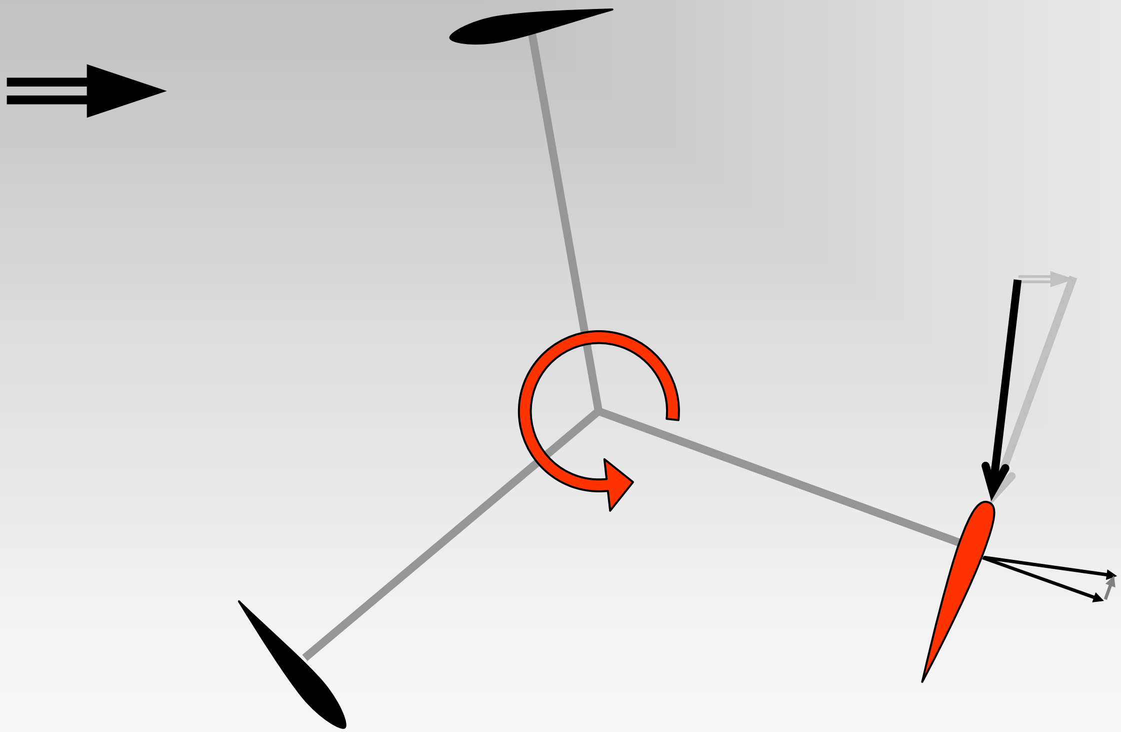


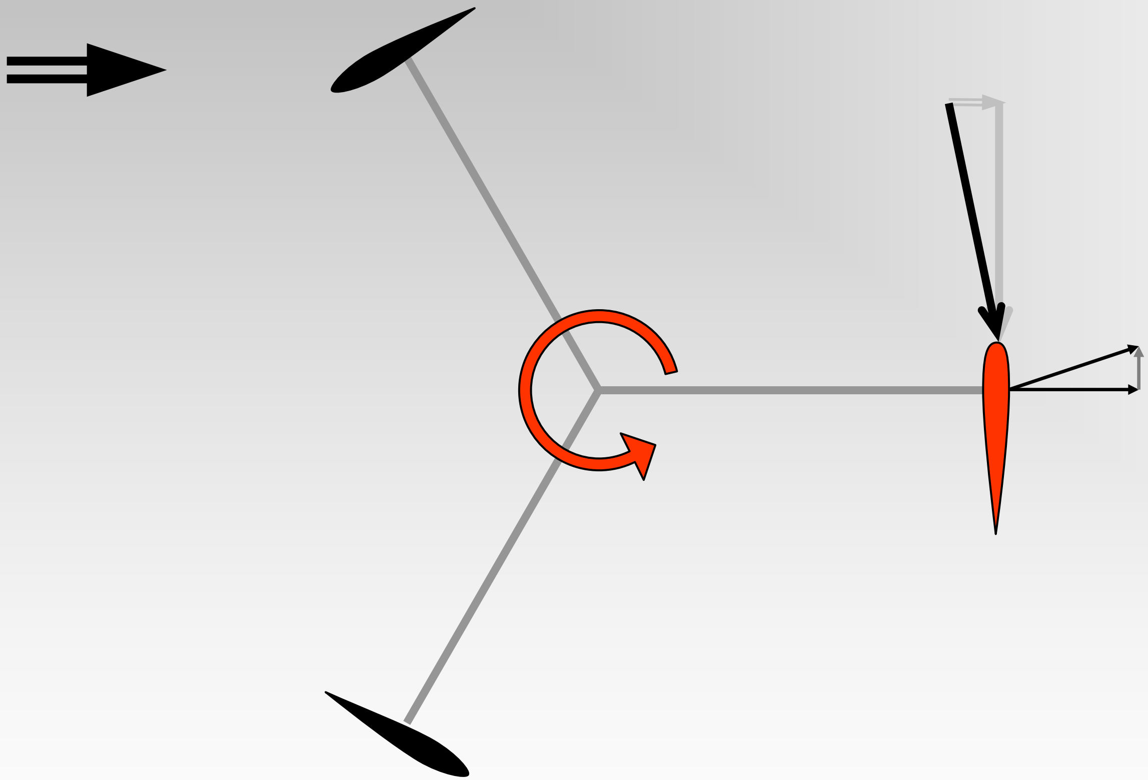


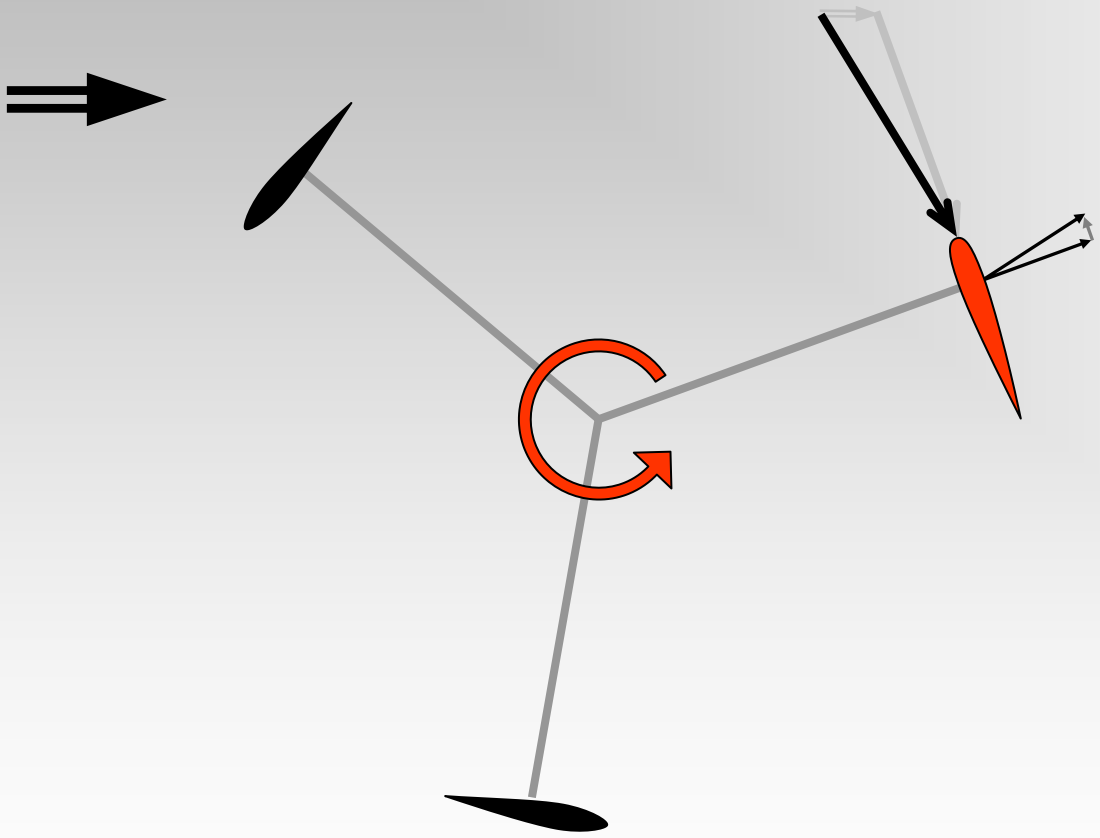


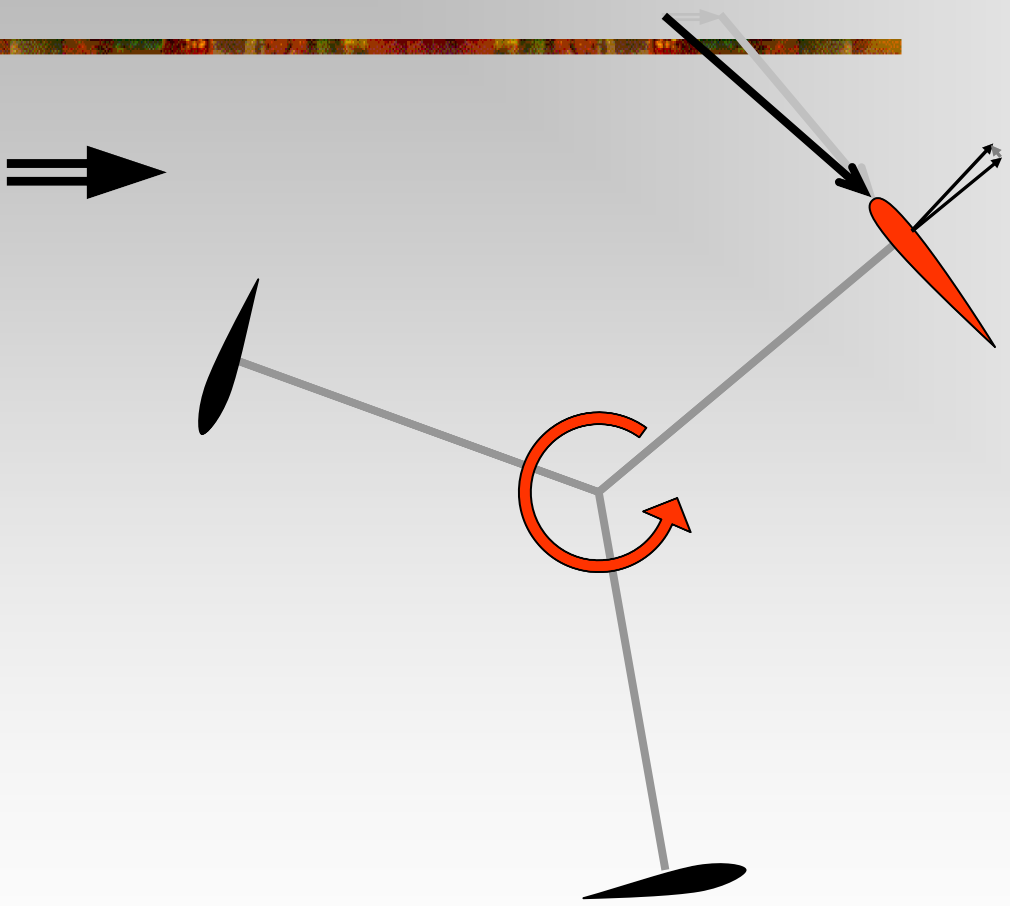


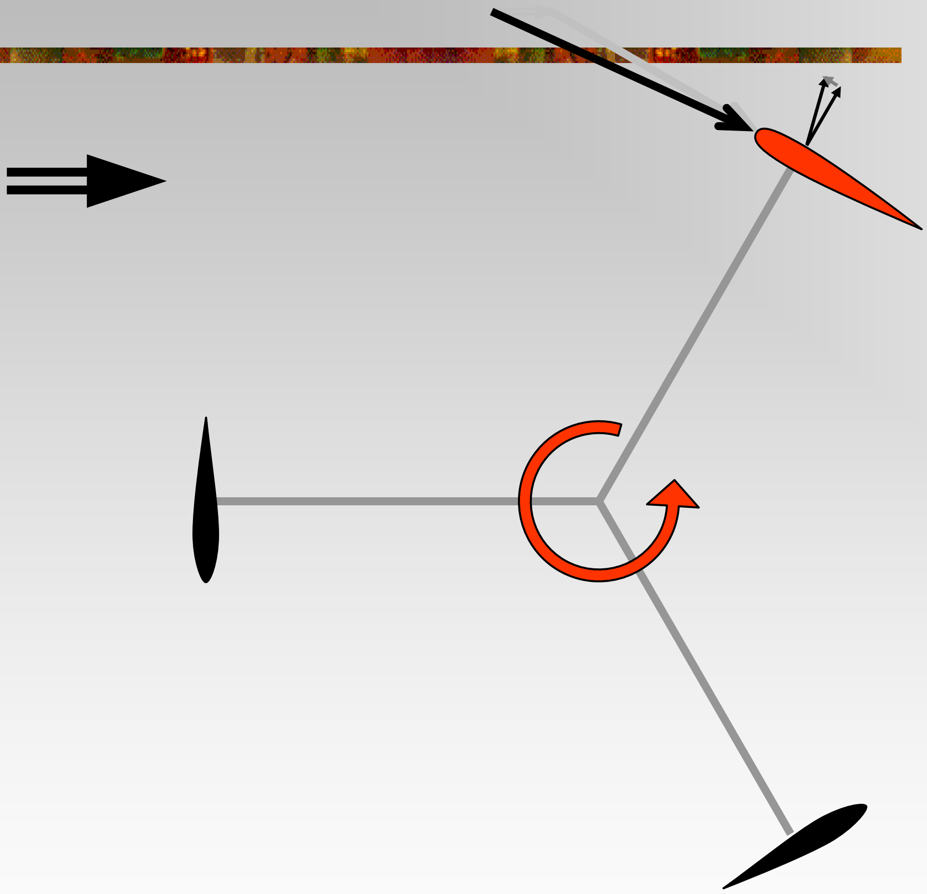


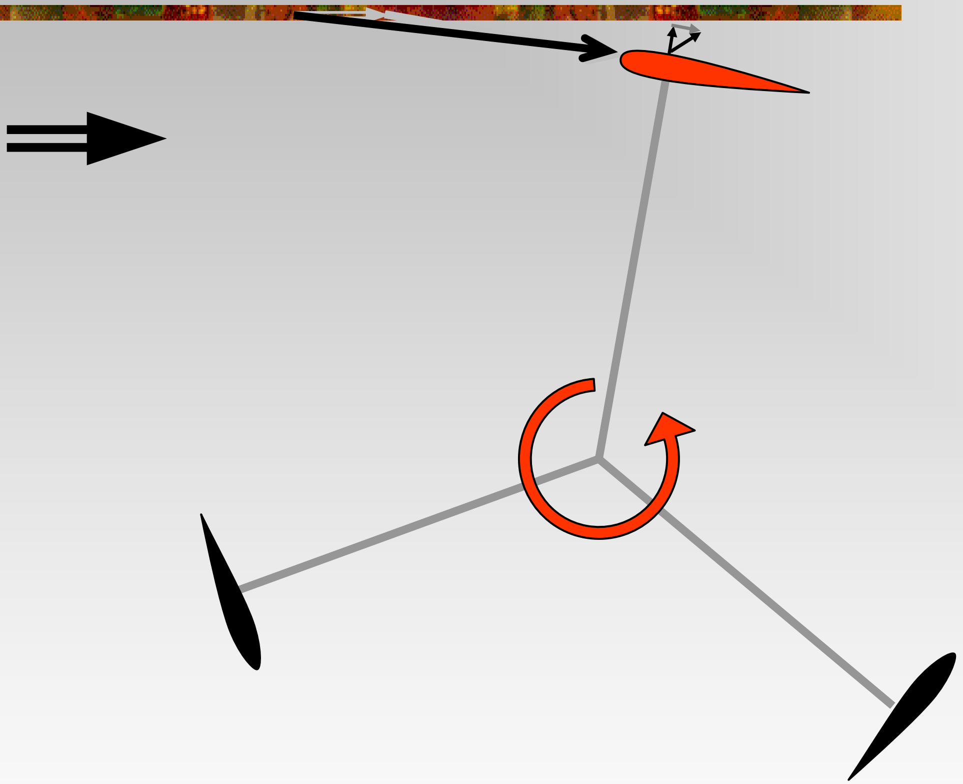


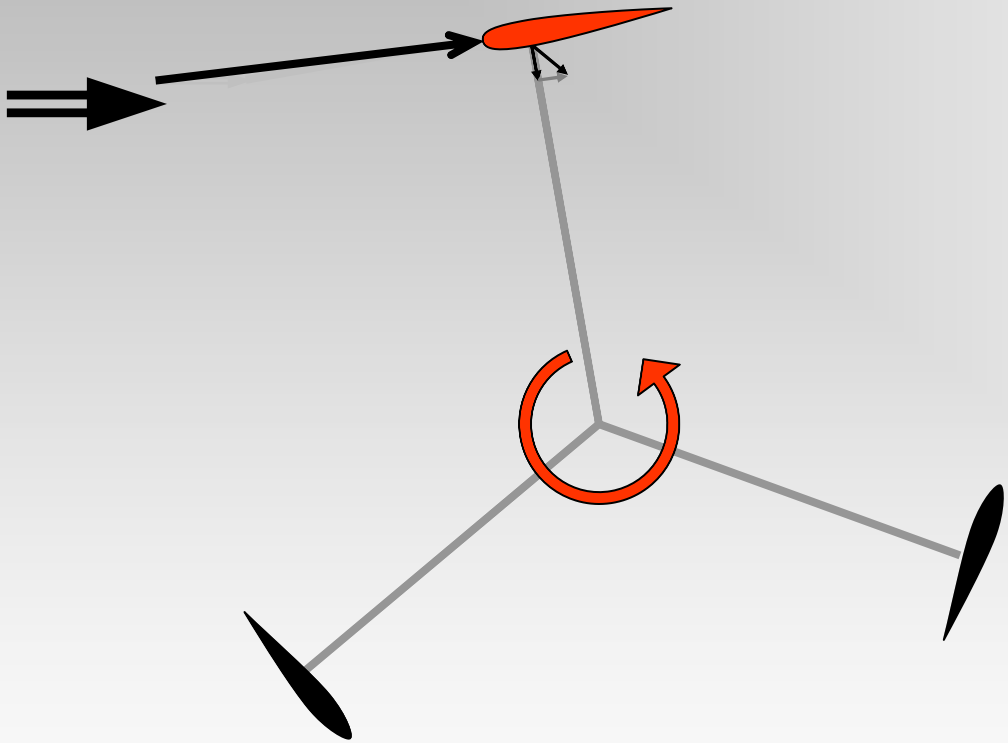


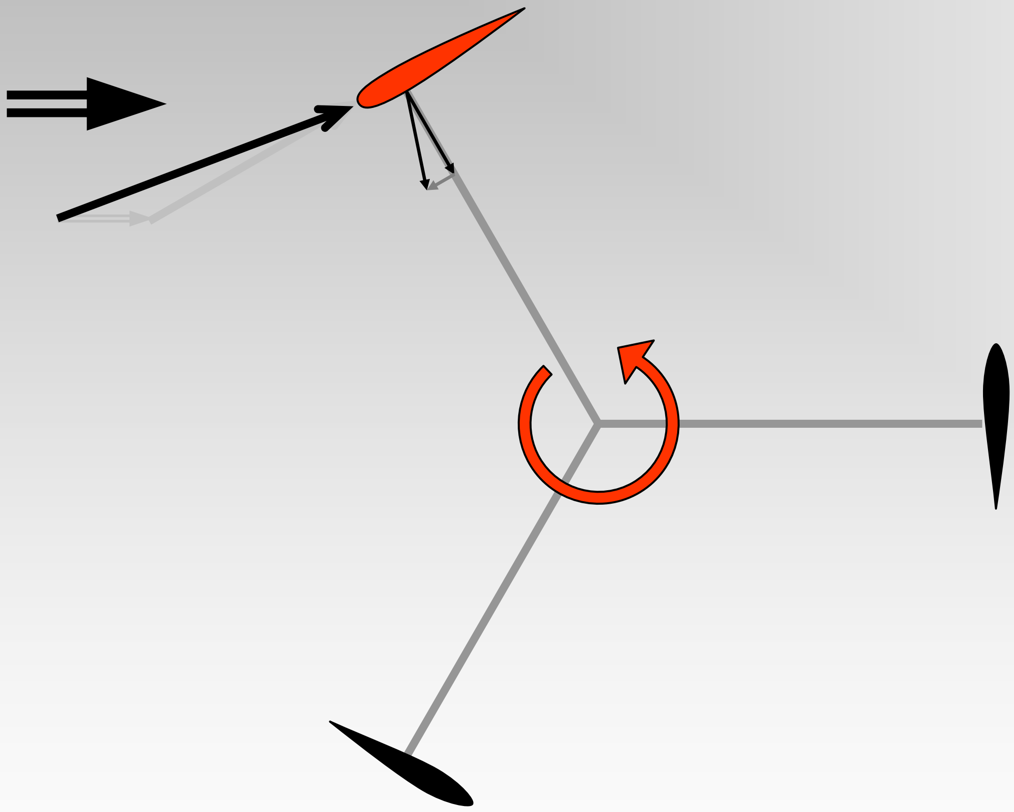


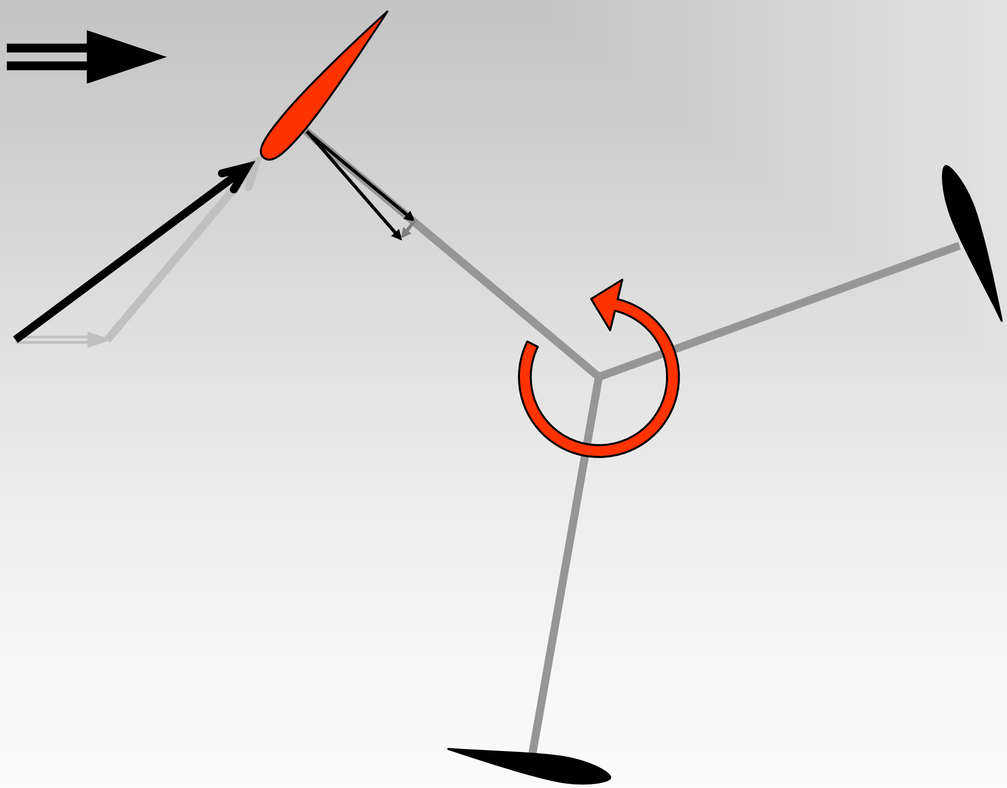


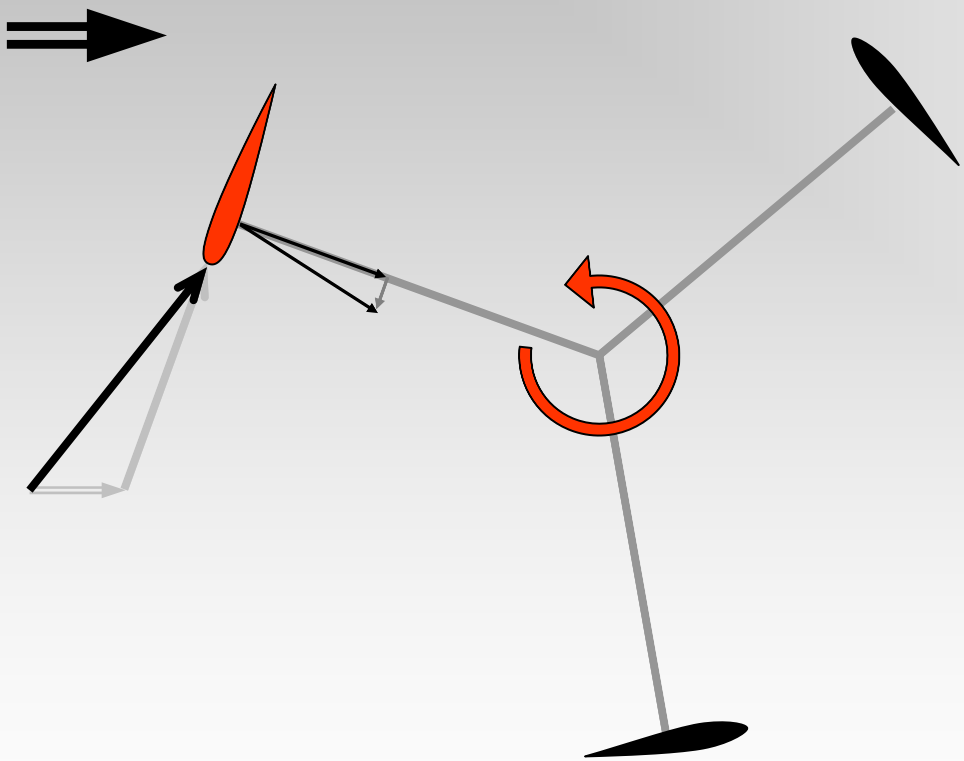


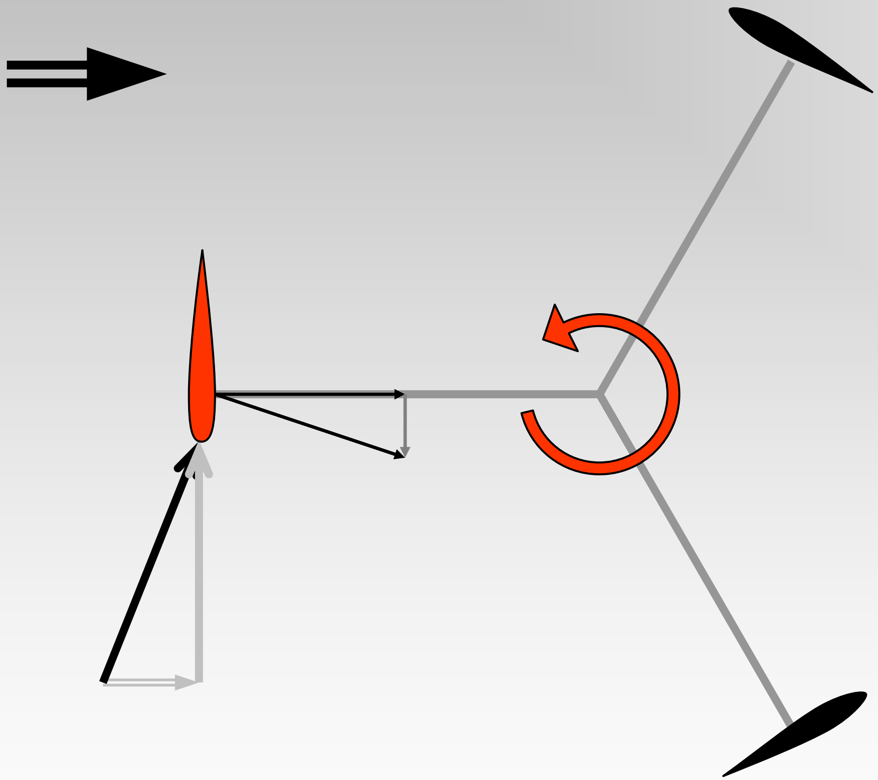












Back

Lift type VAWT

Sandia 34 m testbed
Darrieus “eggbeater”
Source: Sandia National Labs

QR5
Source: Quiet Revolution

Cleanfield 2.5 kW