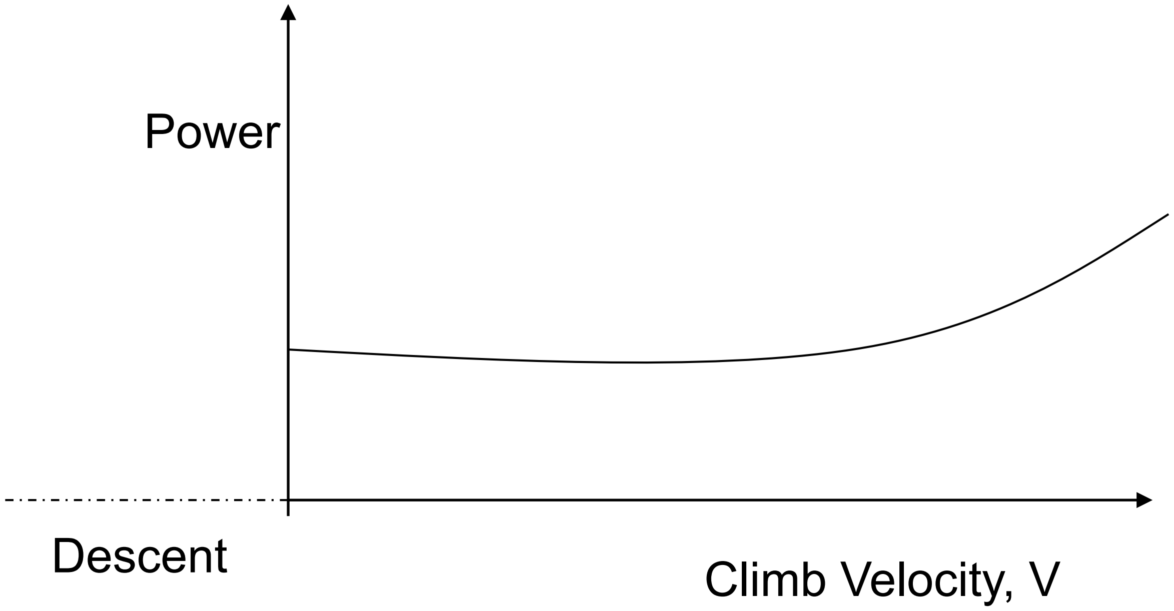
Vertical Descent of Rotors

Background

- We now discuss vertical descent operations, with and without power.
- Accurate prediction of performance is not done. (The engine selection is done for hover or climb considerations. Descent requires less power than these more demanding conditions).
- Discussions are qualitative.
- We may use momentum theory to guide the analysis.

Phase I: Power Needed in Climb and Hover



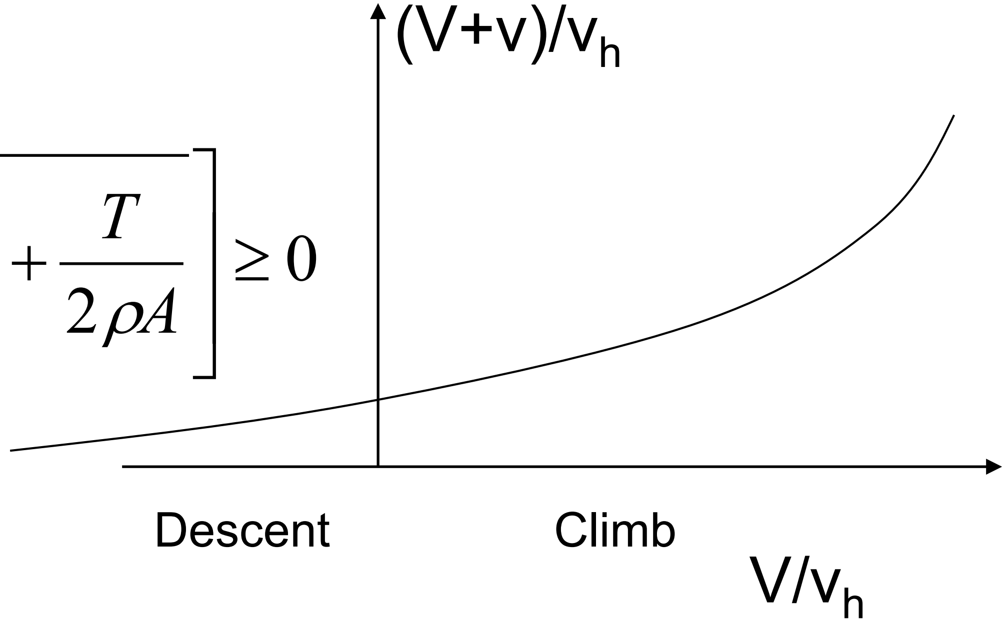
$$P = T\left(V + \mathrm{v}\right)$$

$$= T\left[\frac{V}{2} + \sqrt{\left(\frac{V}{2}\right)^2 + \frac{T}{2\rho A}}\right]$$

Momentum Theory gives incorrect Estimates of Power in Descent

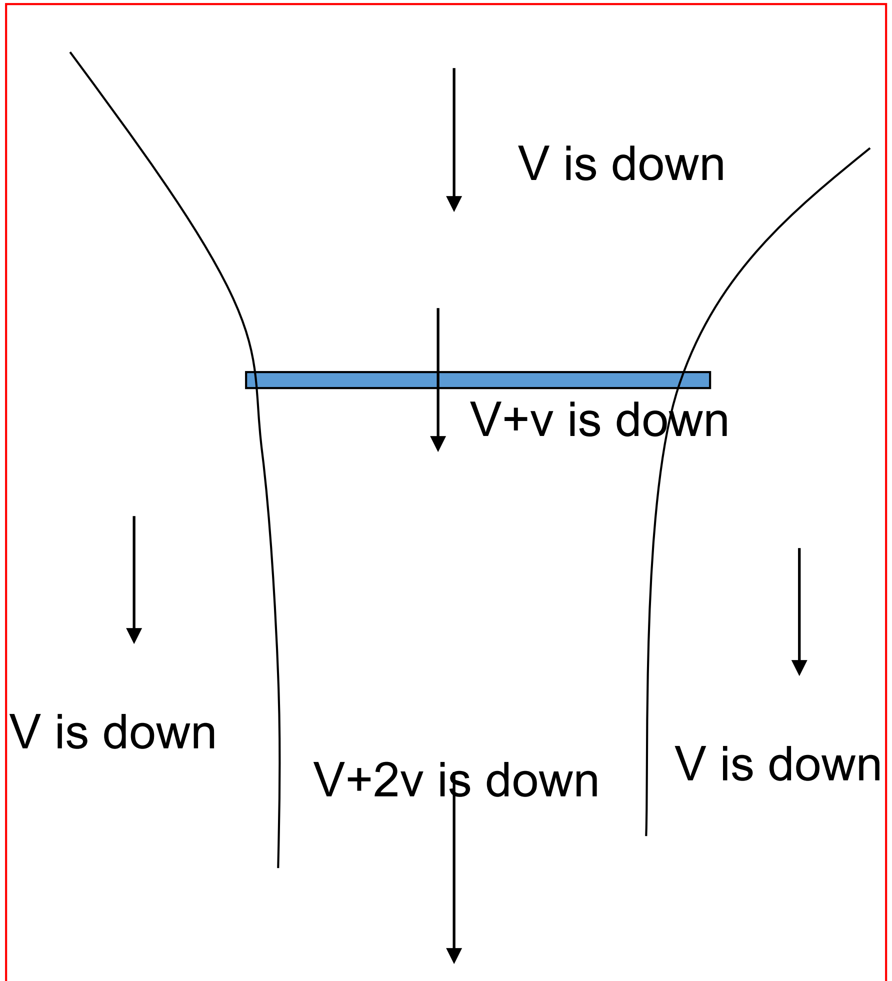
$$P = T(V + \mathrm{v})$$

$$= T\left[\frac{V}{2} + \sqrt{\left(\frac{V}{2}\right)^2 + \frac{T}{2\rho A}}\right] \geq 0$$

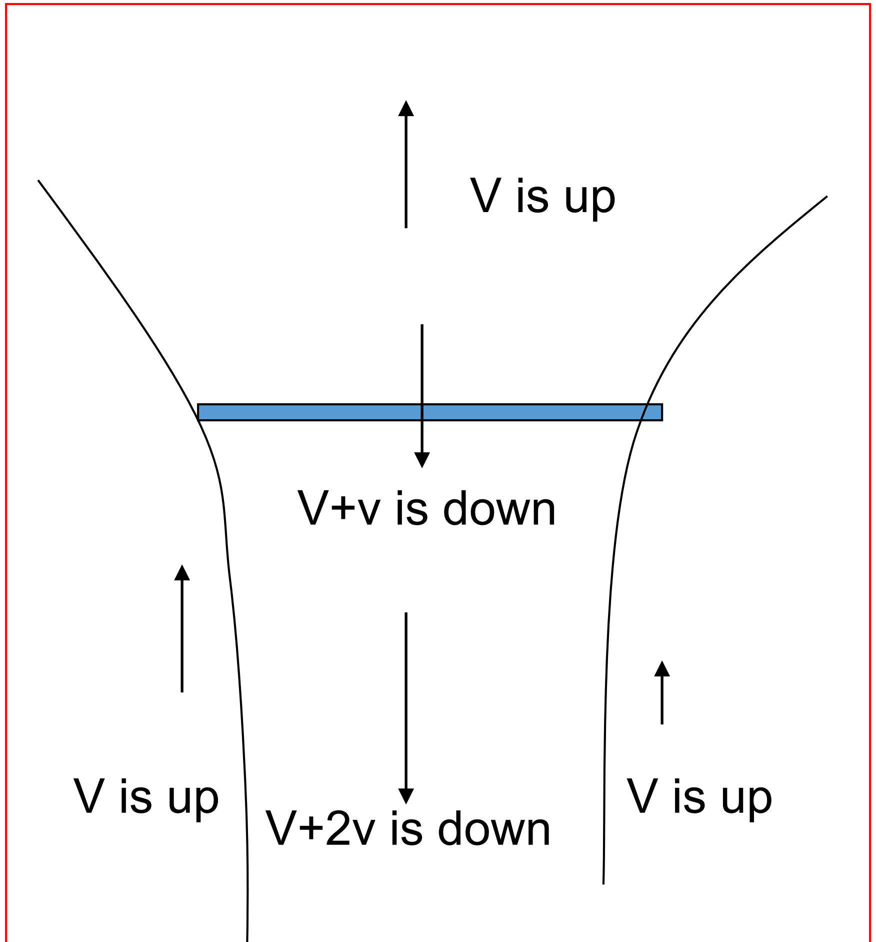


No matter how fast we descend, positive power is still required if we use the above formula.
This is incorrect!

The reason..



Climb or hover
Physically acceptable Flow



Descent: Everything inside
Slipstream is down
Outside flow is up

Non-Dimensional Form

It is convenient to non-dimensionalize these graphs, so that universal behavior of a variety of rotors can be studied.

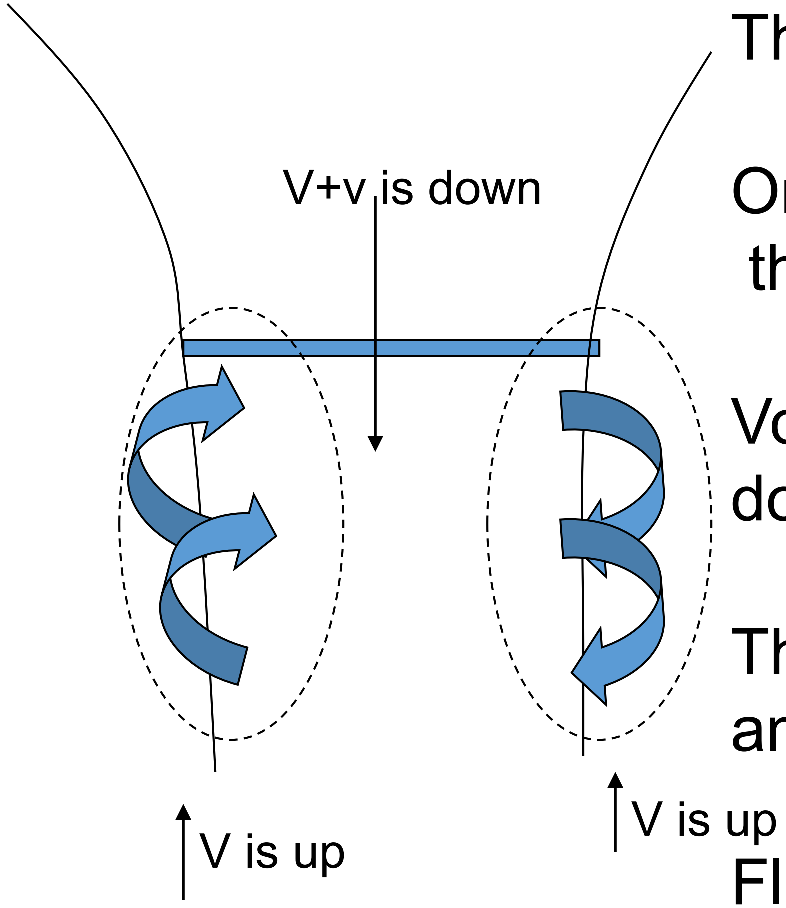
Climb or descent velocity is non-dimensionalized by hover inflow velocity $v_h = \sqrt{\frac{T}{2\rho A}}$

Power $T(V+v)$ is non-dimensionalized by Tv_h

In reality..

- The rotor in descent operates in a number of stages, depending on how fast the vertical descent is in comparison to hover induced velocity.
    - Vortex Ring State
    - Turbulent Wake State
    - Windmill Brake State

Vortex Ring State
(V is up, V+v is down, V+2v is down)



The rotor pushes tip vortices down.

Oncoming air at the bottom pushes them up

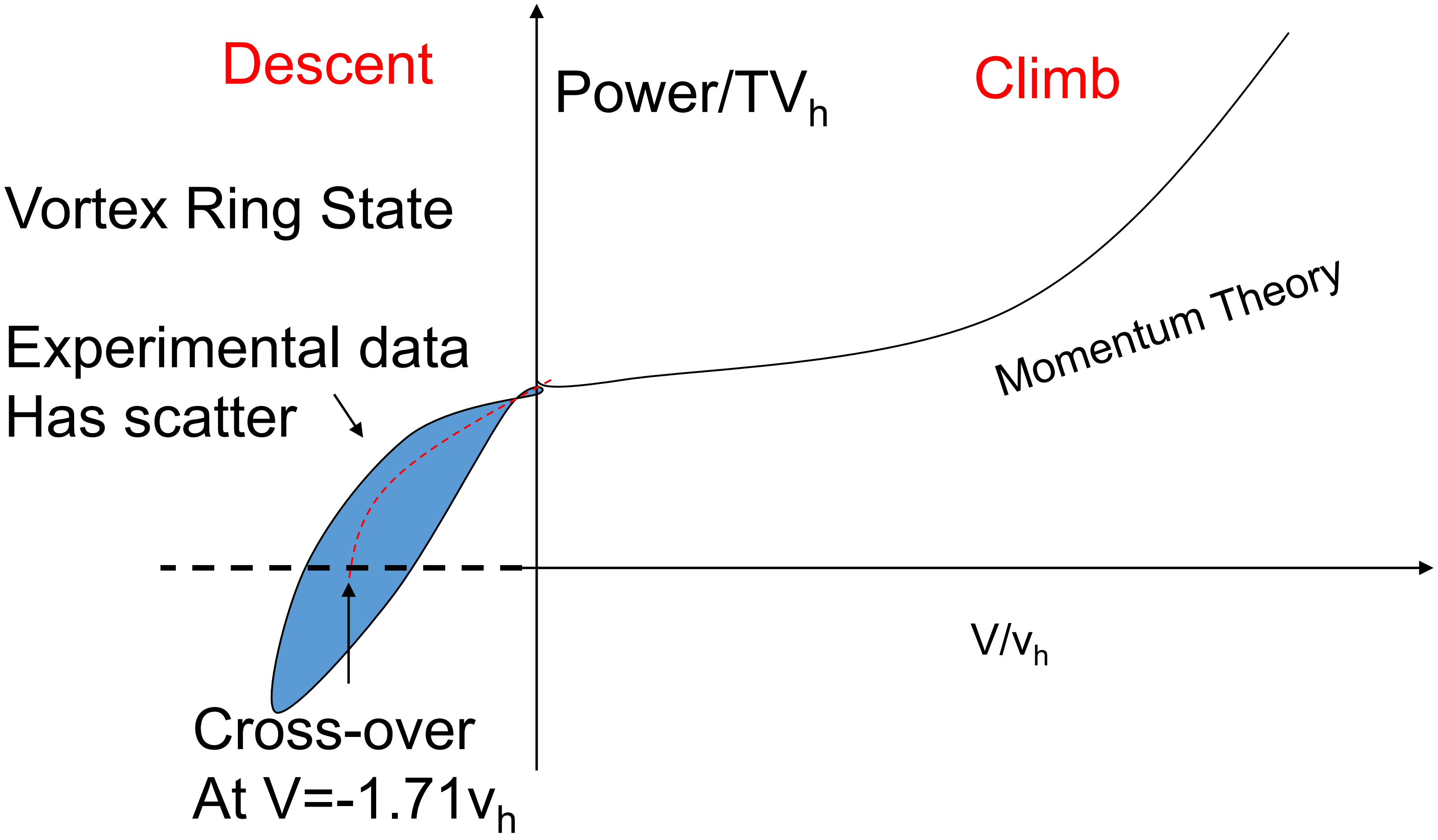
Vortices get trapped in a donut-shaped ring.

The ring periodically grows and bursts.

Flow is highly unsteady.

Can only be empirically analyzed.

Performance in Vortex Ring State

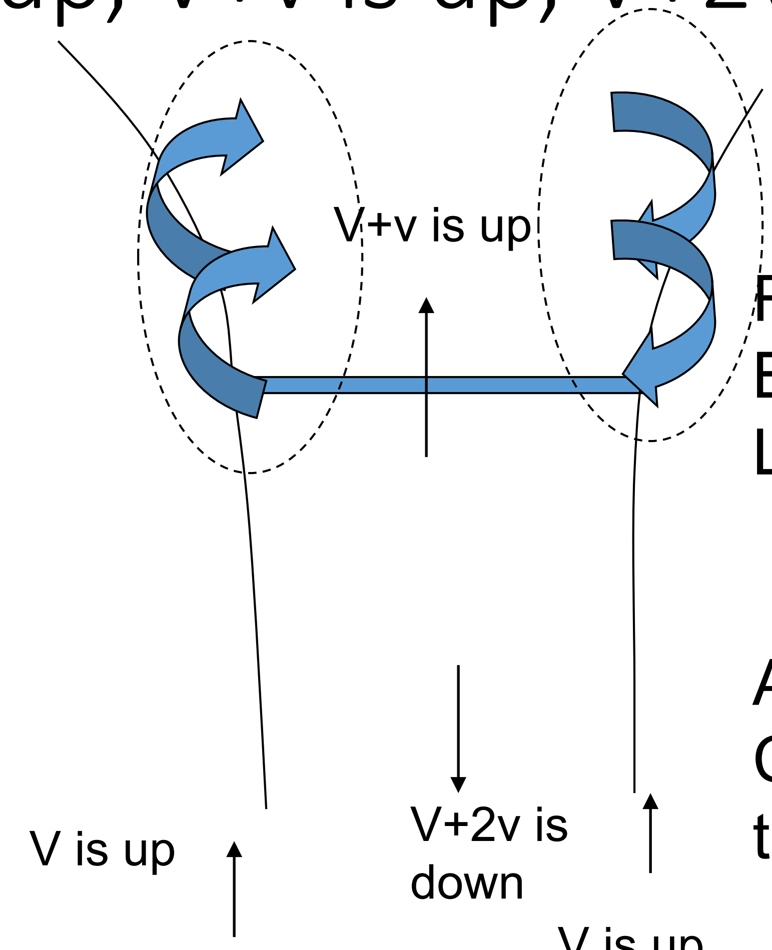


Vortex Ring State

Experimental data
Has scatter

Cross-over
At V=-1.71v$_h$

Turbulent Wake State
(V is up, V+v is up, V+2v is down)

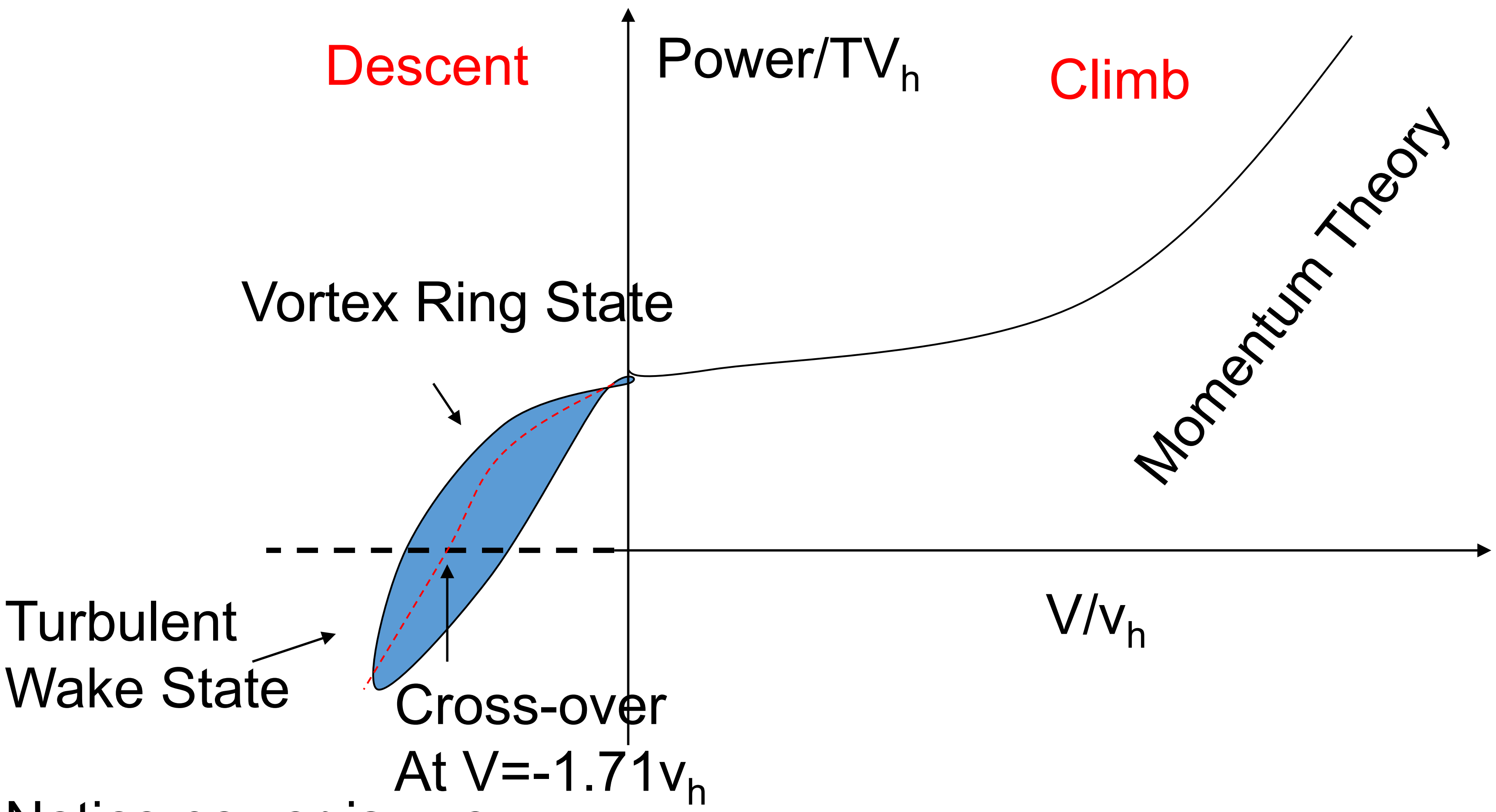


Rotor looks and behaves like a bluff Body (or disk). The vortices look Like wake behind the bluff body.

Again, the flow is unsteady,
Can not analyze using momentum theory

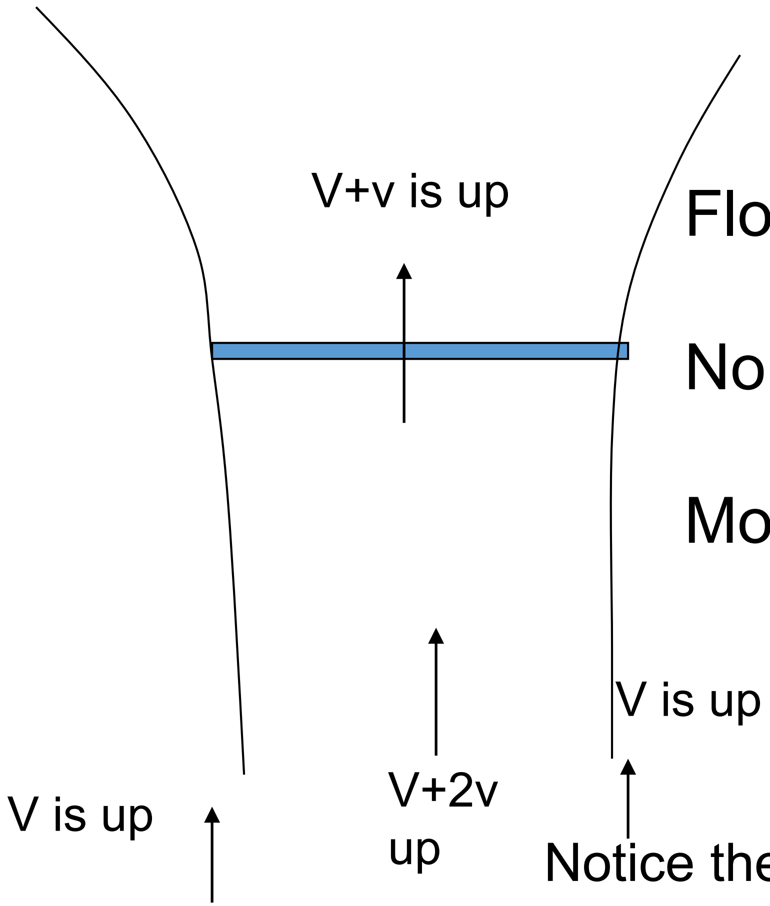
Need empirical data.

Performance in Turbulent Wake State



Notice power is –ve
Engine need not supply power

Wind Mill Brake State (V is up, V+v is up, V+2v is up)



Flow is well behaved.

No trapped vortices, no wake.

Momentum theory can be used.

$$T = -2\rho A v(V+v)$$

Notice the minus sign. This is because v (down) and V+v (up) have opposite signs. The product must be positive..

Power is Extracted in Wind Mill Brake State

We can solve the equation :

$$\mathrm{T} = -2\rho A \mathrm{v}(\mathrm{V} + \mathrm{v})$$

to get

$$\mathrm{v} = -\frac{\mathrm{V}}{2} - \sqrt{\left(\frac{V}{2}\right)^2 - \frac{T}{2\rho A}}$$

$$P = T(V + \mathrm{v})$$

Sign convention :

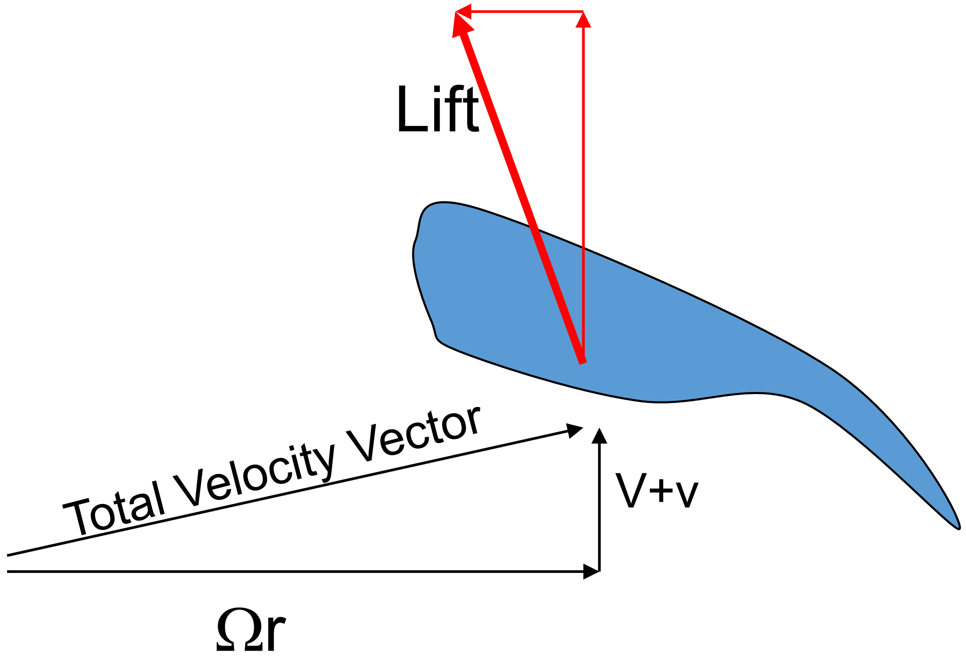
$\mathrm{V} > 0$ is climb, $\mathrm{V} < 0$ is descent

$\mathrm{P} > 0$ means power is consumed

$\mathrm{P} < 0$ means power is extracted.

In this case, power is extracted from the freestream, as in a wind mill.

Physical Mechanism for Wind Mill Power Extraction

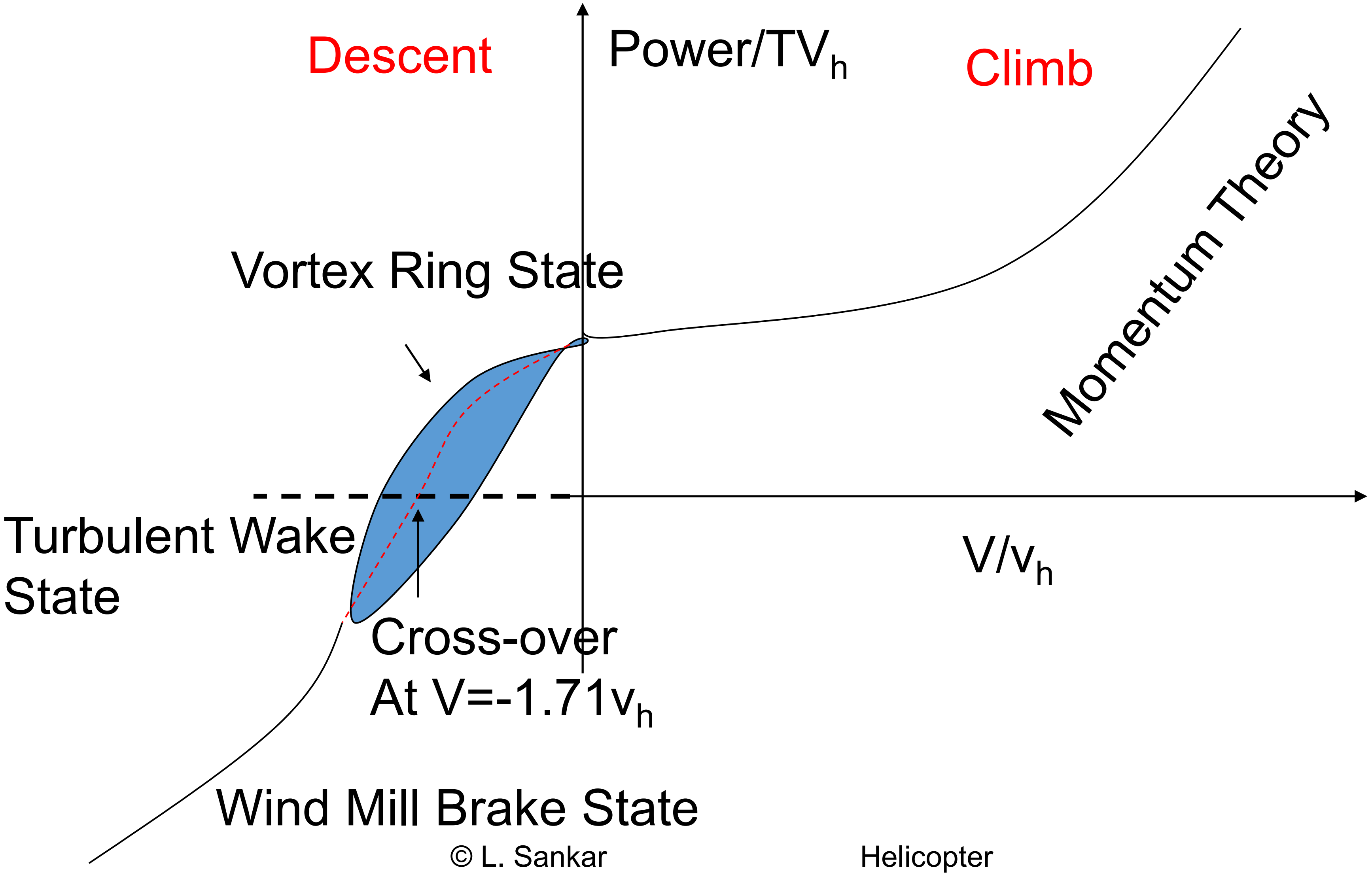


The airfoil experiences an induced thrust, rather than induced drag!

This causes the rotor to rotate without any need for supplying power or torque. This is called autorotation.

Pilots can take advantage of this if power is lost.

Complete Performance Map



Consider the cross-over Point

If the vehicle descents at this speed, power is neither supplied, nor extracted.

$V = -1.7 v_h$

We can estimate the drag coefficient of the rotor as follows:

$$T = \frac{1}{2} \rho A C_D (1.7 v_h)^2$$

Use $v_h = \sqrt{\dfrac{T}{2\rho A}}$

$C_D \cong 1.4$

The rotor has the same drag coefficient as a parachute with equivalent area A.

As good as a parachute!!!