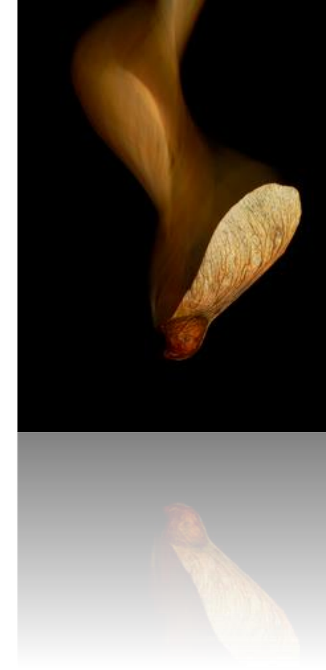
Aerodynamics 2 - Rotorcraft Aerodynamics



Fundamentals of Vertical Flight (straight up and down)
Lecture 3

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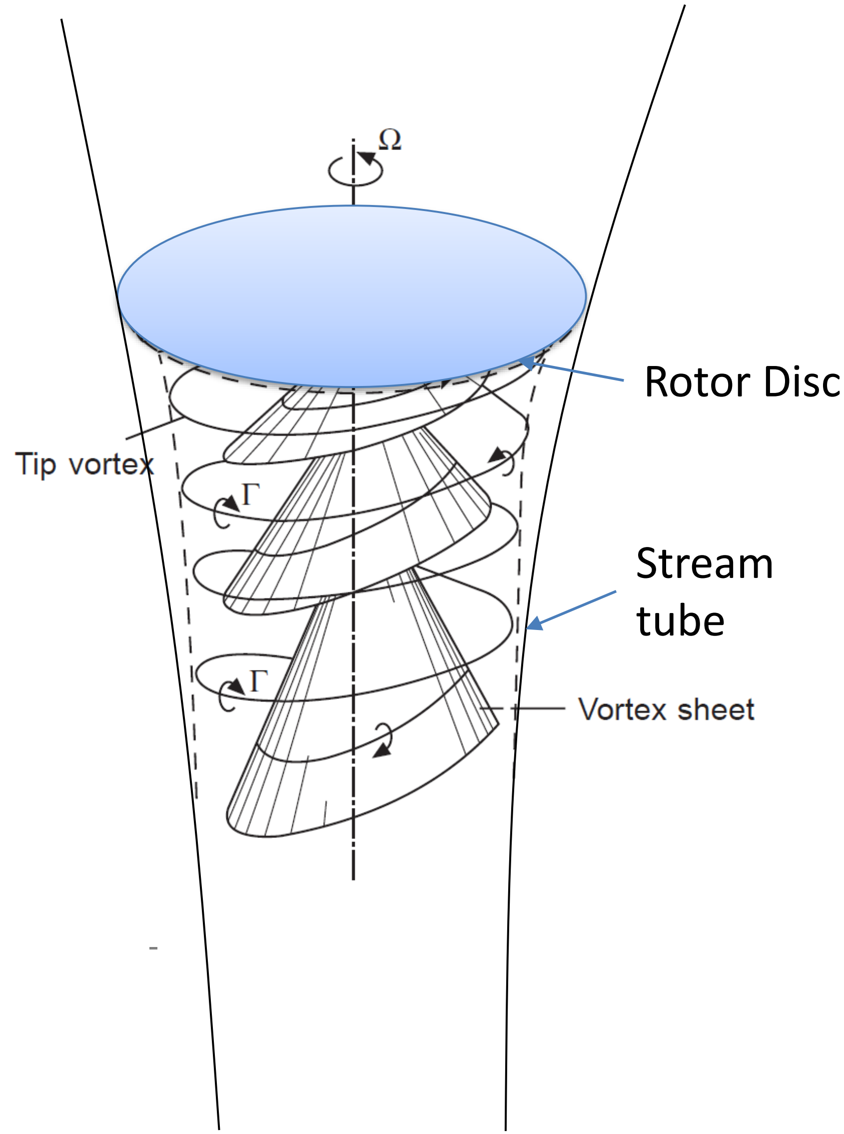
Axial Flight

Hover ... Climb ... Descent

- momentum analysis
- Axial flow states
- Universal Induced Velocity diagram

Helicopter Aerodynamics in Axial Flight



Actuator Disc (Momentum) Theory

The Lifting Rotor in it's most simplistic form is a Propeller.

Mechanical energy (in the form of rotating blades) is used to accelerate (*a*) a mass (*m*) of air.

Newton's law (every action has a reaction), states ***F=ma***, where ***F***, is the rotor thrust (***T***).

Applying Bernoulli's equation:

$$H_0 = P_0 + {}^1\!/_2\,\rho V^2 = P_1 + {}^1\!/_2\,\rho (V+v)^2$$
$$H_1 = P_0 + {}^1\!/_2\,\rho (V+v_1)^2 = P_1 + P' + {}^1\!/_2\,\rho (V+v)^2$$

Subtracting H_0 from H_1 results in

$$H_1 - H_0 = {}^1\!/_2\,\rho\,(2Vv_1 + v_1^2) = P'$$

However, the Thrust=change of axial momentum per unit time

$$\frac{T}{A} = P' = \rho(V+v)v_1$$

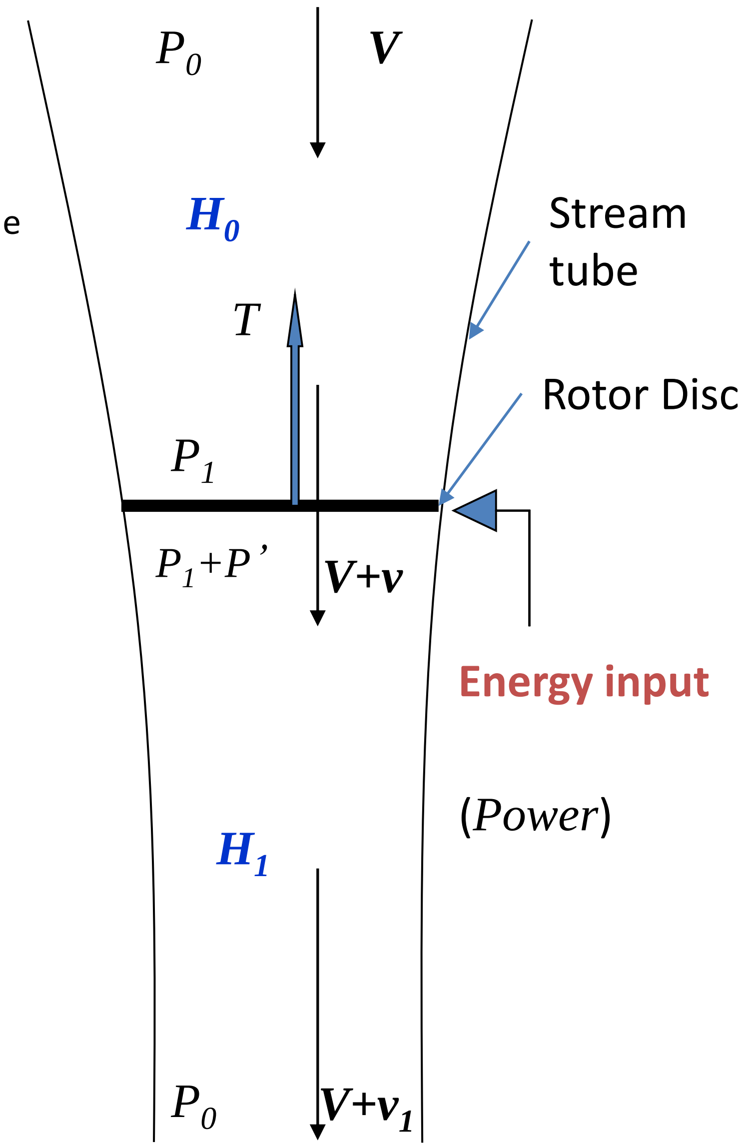
Where ρ is the air density and A is the rotor disc area

Hence

$$\frac{v_1}{2} = v \quad or \quad v_1 = 2v$$

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

Power: $P = T(V+v)$



Momentum Theory in Hover

Or a lifting rotor

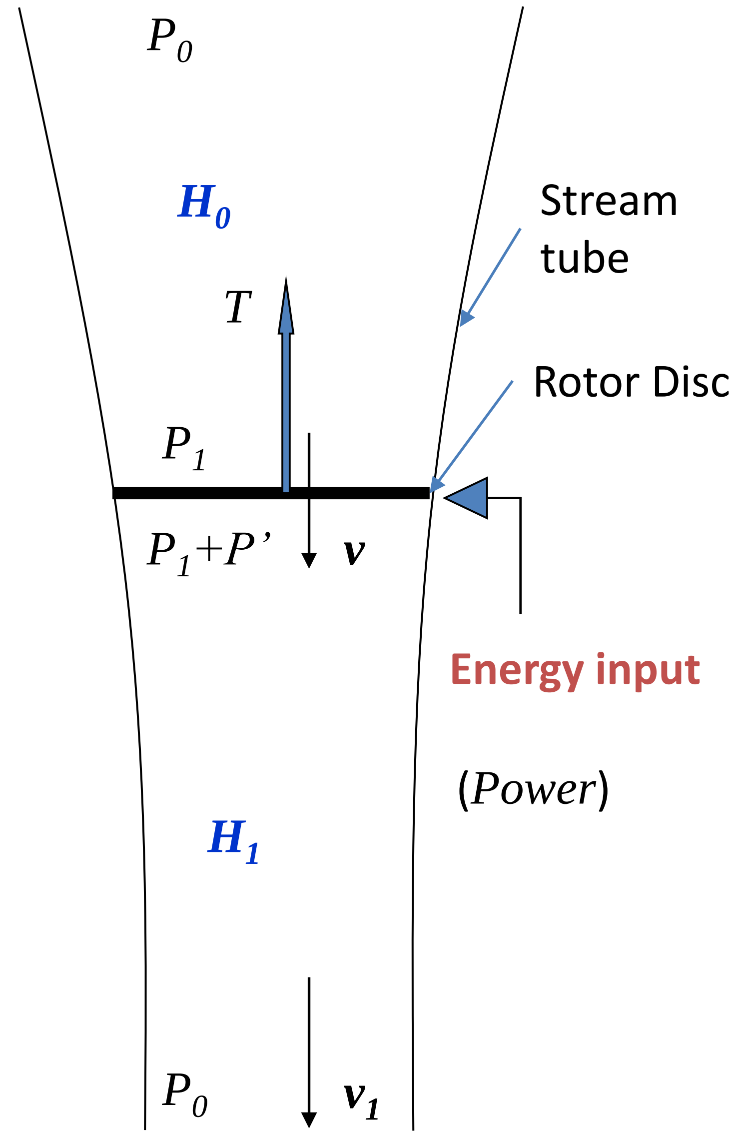
in **hover**, when

the onset velocity

V =0

$$\boxed{v_h = \sqrt{\frac{T}{2\rho A}}}$$

$P_h = T v_h$ Hence $$\boxed{P_h = \frac{T^{3/2}}{\sqrt{2\rho A}}}$$

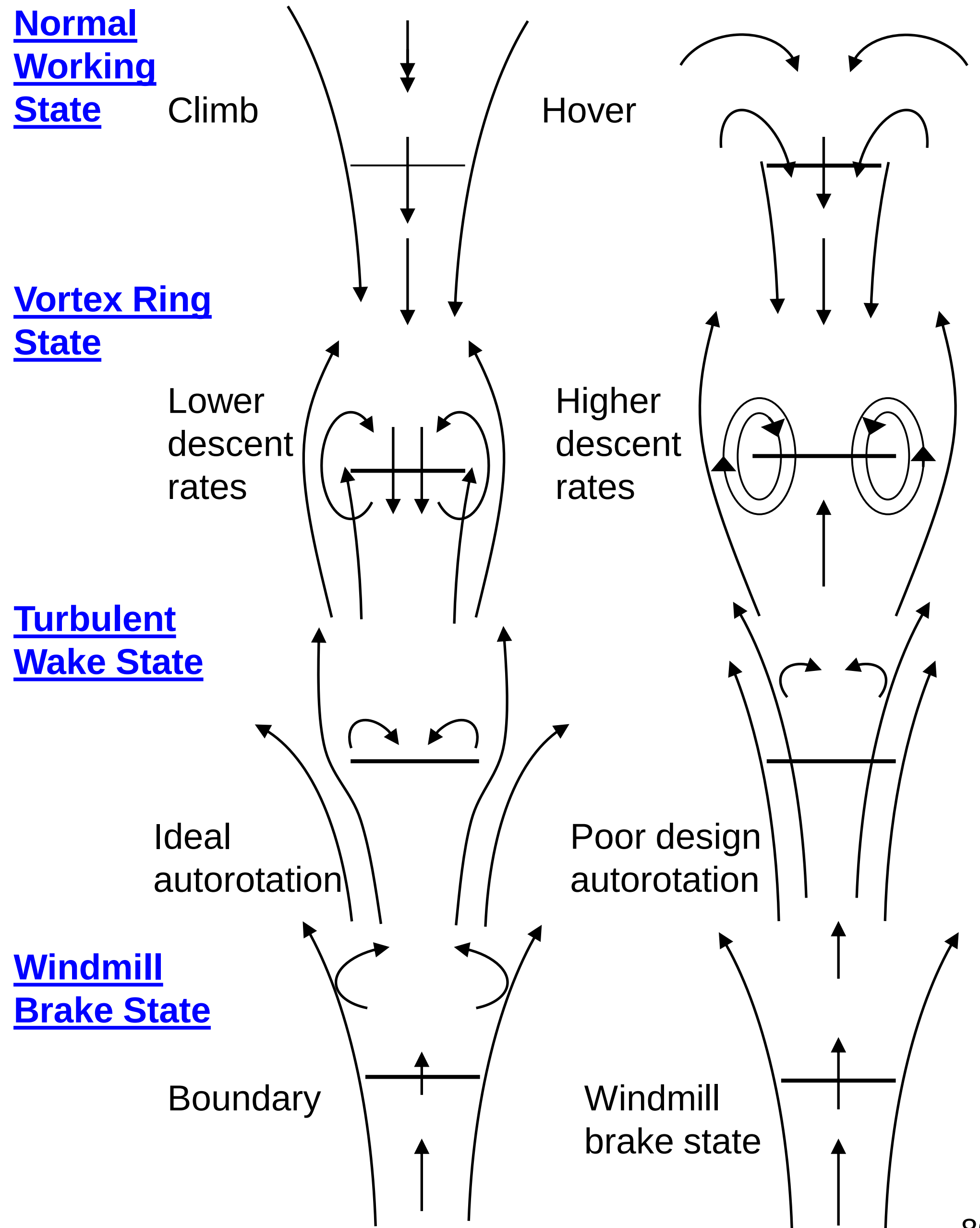


AXIAL FLOW STATES

The vertical climb and hover states (and to a certain extent the slow decent) are easily analysed by momentum considerations, as already discussed.

Higher rates of decent can be problematic, both analytically (as the stream tube no longer exists) and in piloting the craft.

Following a total engine failure the helicopter pilot will descend the aircraft into the upper region of the turbulent wake state.

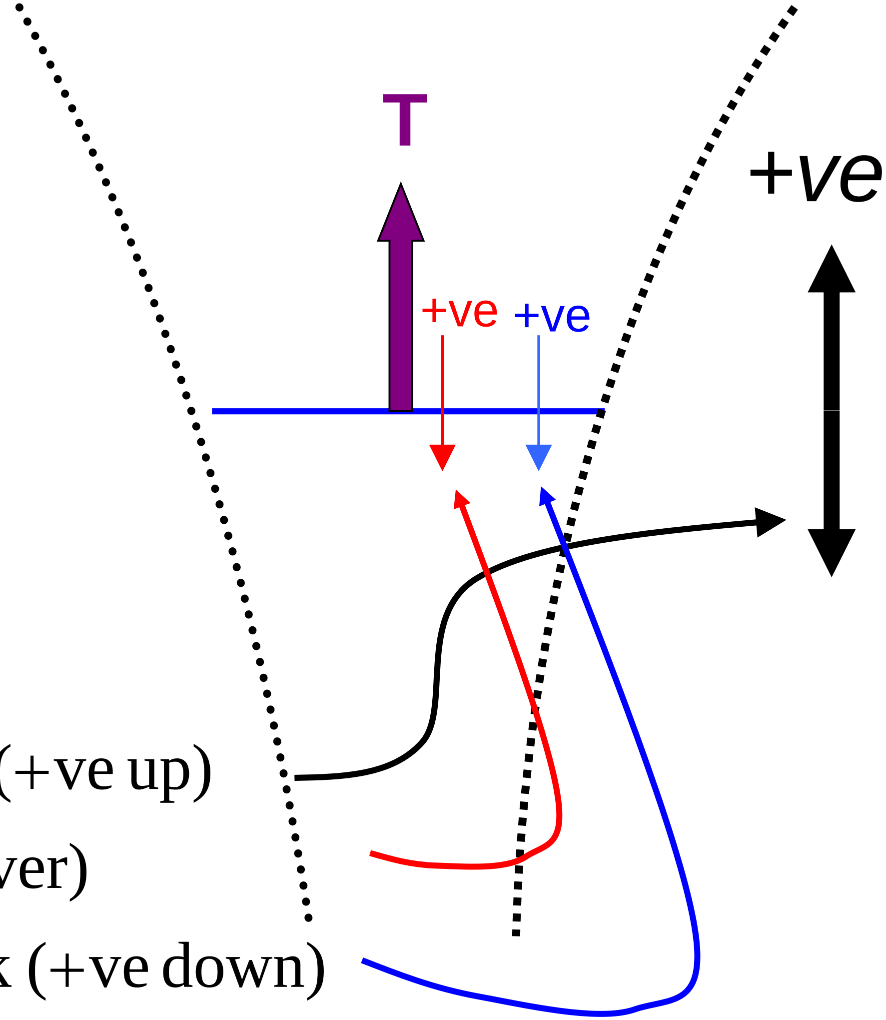


THE OPERATING STATES

The Rotor in BLUE

A Constant and always POSITIVE

THRUST is produced in each state.



V_V is the Aircraft Vertical Velocity (+ve up)

v is the induced velocity, v_h (in hover)

U is the flow through the rotor disk (+ve down)

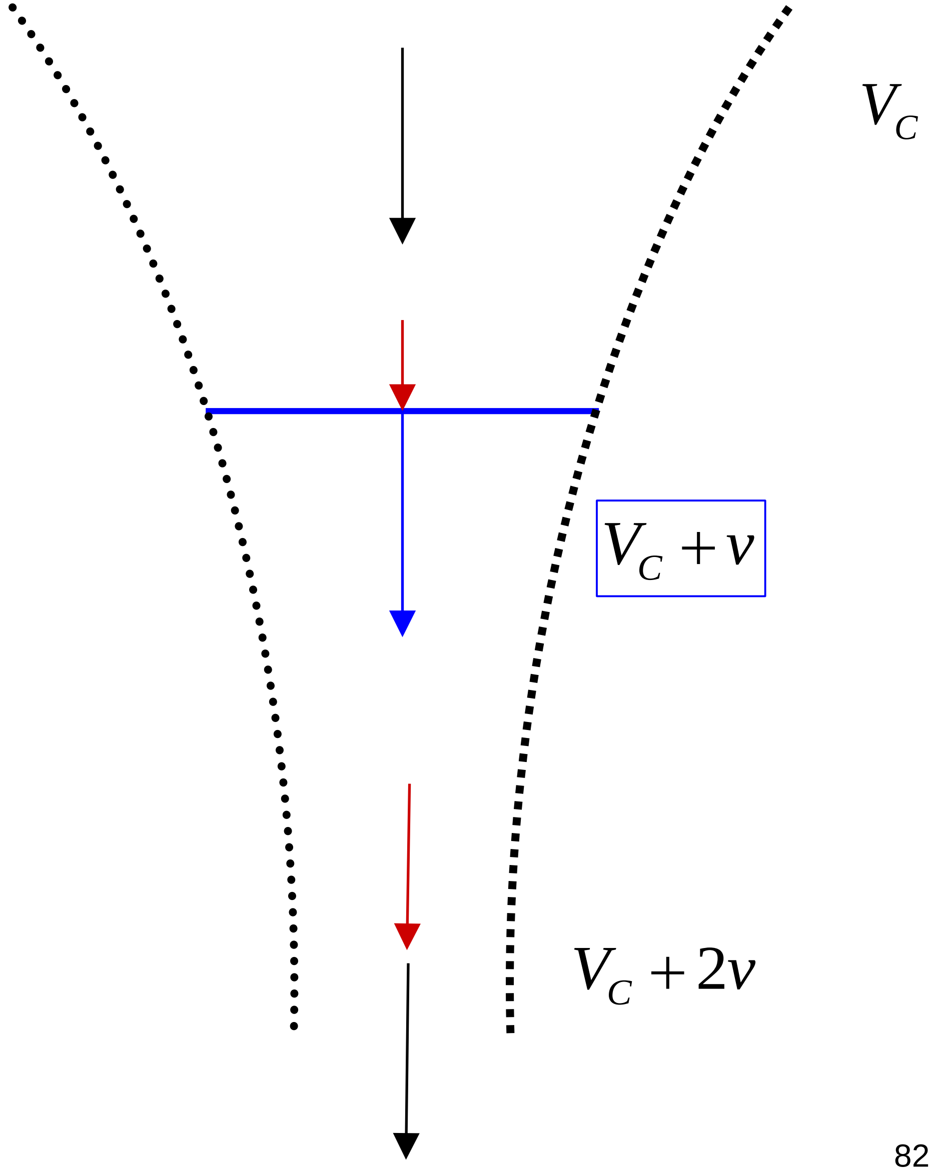
Note: V_C is the air flow velocity due to Aircraft Vertical motion ($= -V_V$)

NORMAL WORKING STATE

The Rotor in CLIMB

Momentum Theory applies as

an effective stream tube exists.



$$V_V > 0$$

$$v < v_h$$

$$U > v$$

NORMAL WORKING STATE

Rotor in HOVER

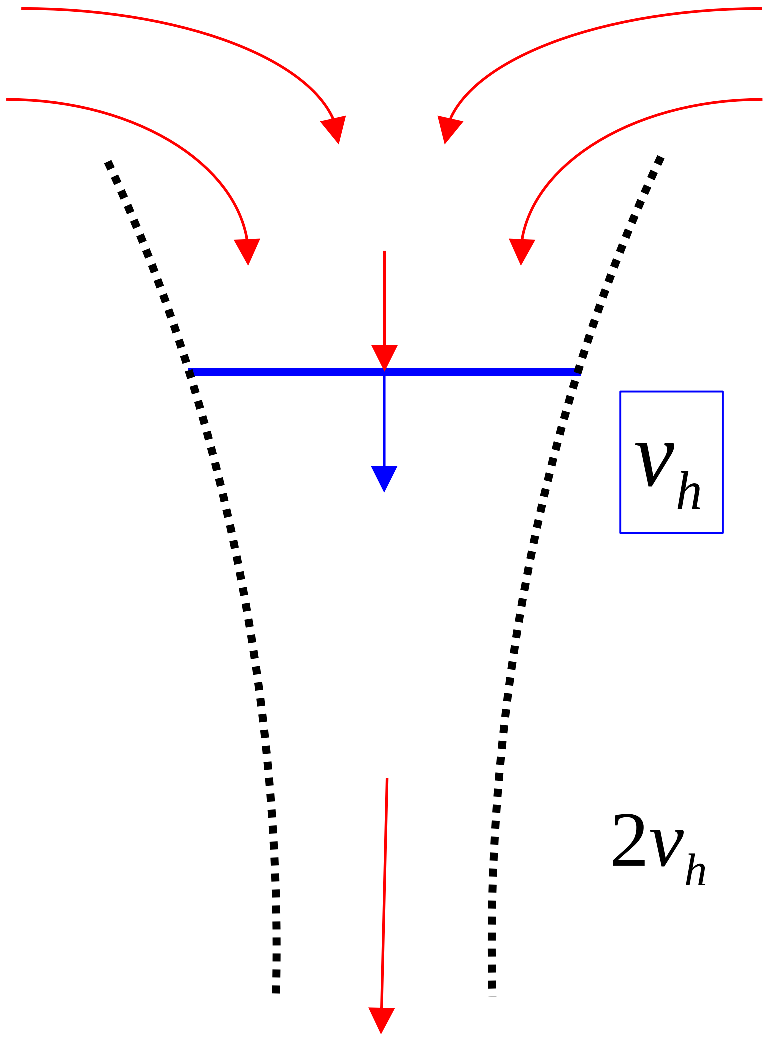
Momentum Theory applies as

an effective stream tube exists.

$$V_V = 0$$

$$v = v_h$$

$$U = v$$



VORTEX RING STATE

Rotor in VERY SLOW DESCENT

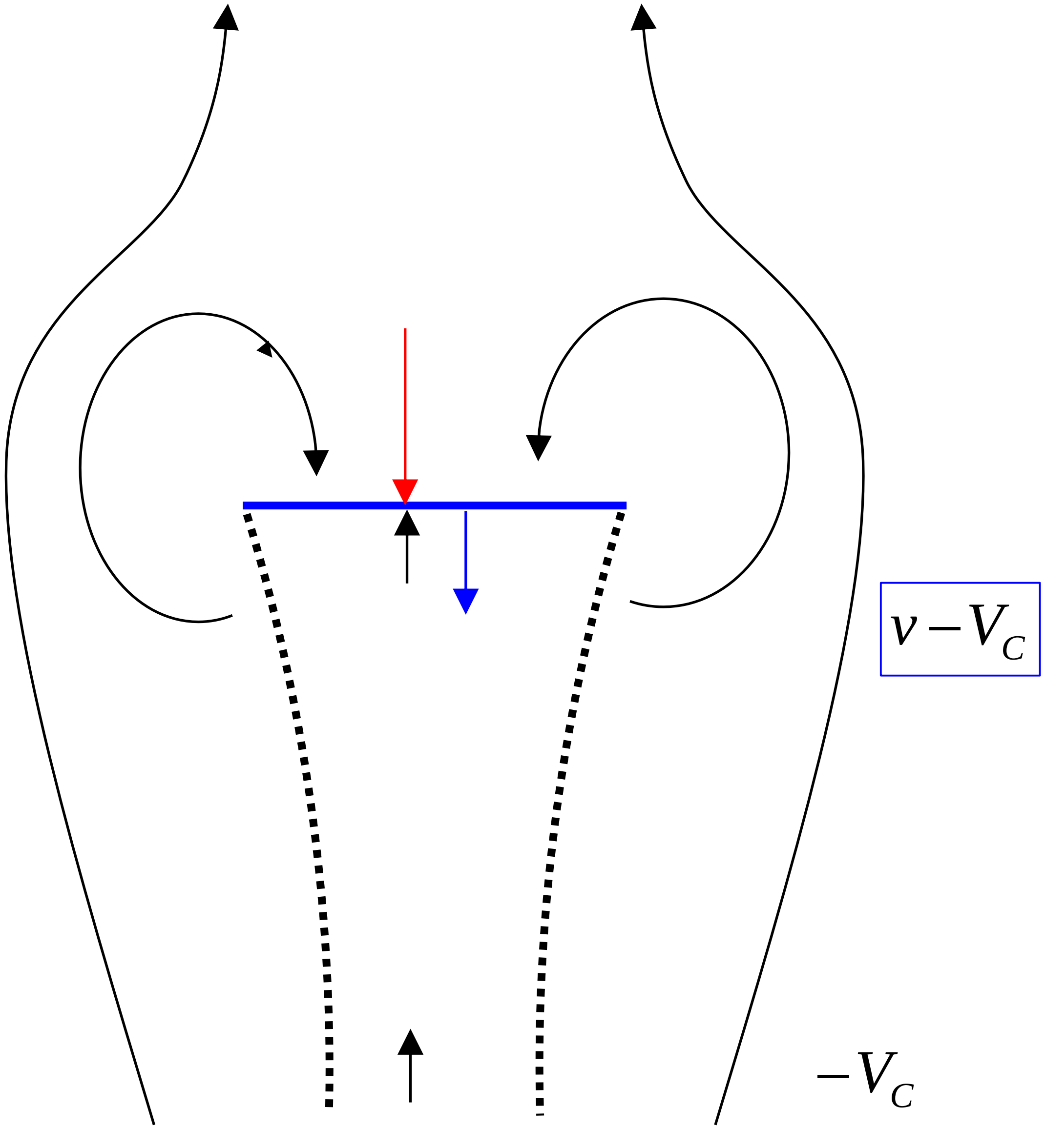
Momentum Theory applies as

an effective stream tube exists.

$$0 > V_V \geq \left(\frac{-v_h}{2} \right)$$

$$v > v_h$$

$$U < v$$



VORTEX RING STATE

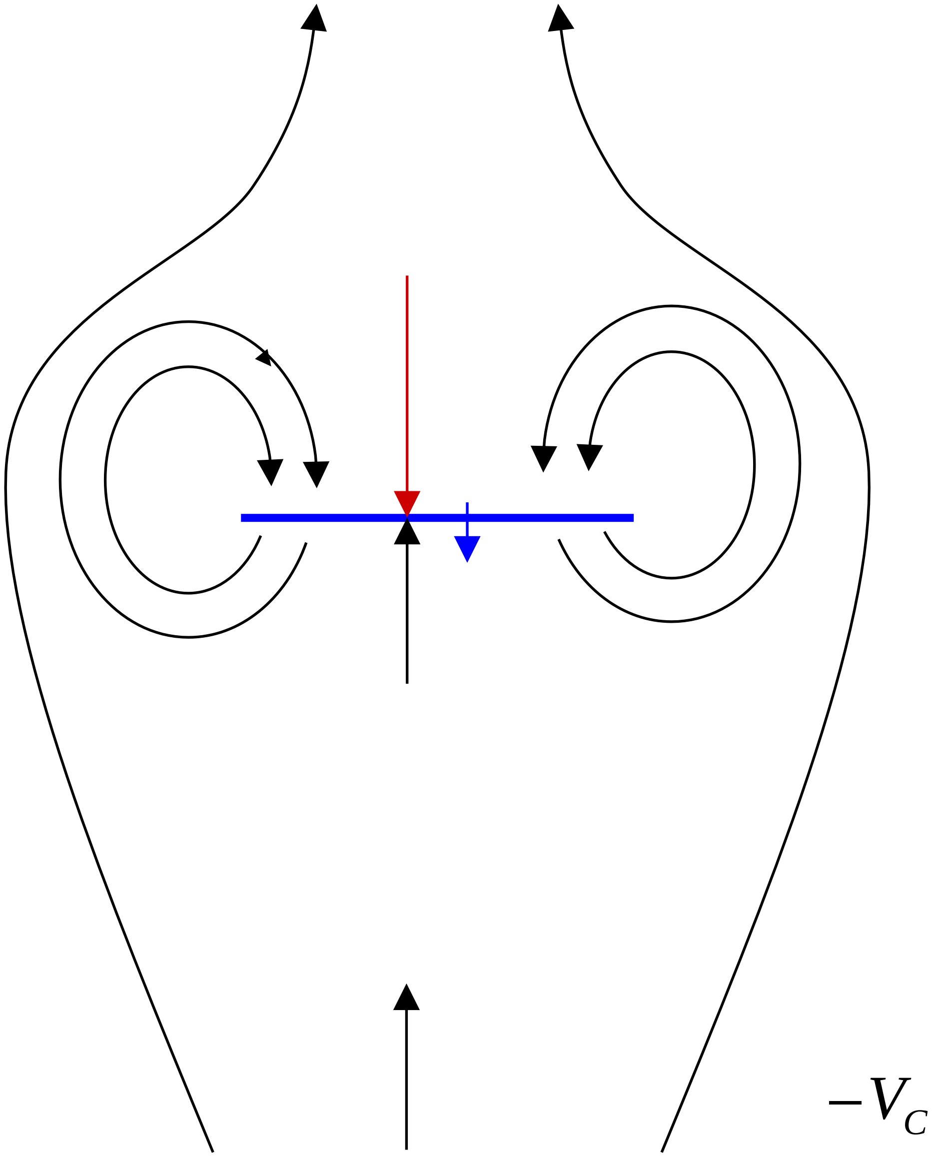
Rotor in SLOW DESCENT

Momentum Theory does not apply as no effective stream tube exists.

$$\left(\frac{-v_h}{2}\right) \geq V_V \geq -v_h$$

$$v \;\; >> v_h$$

$$U < v$$



TURBULENT WAKE STATE

Rotor in MODERATE DESCENT

Momentum Theory does not apply as no effective stream tube exists.

$$-v_h \geq V_V \geq -\tfrac{3}{2} v_h$$

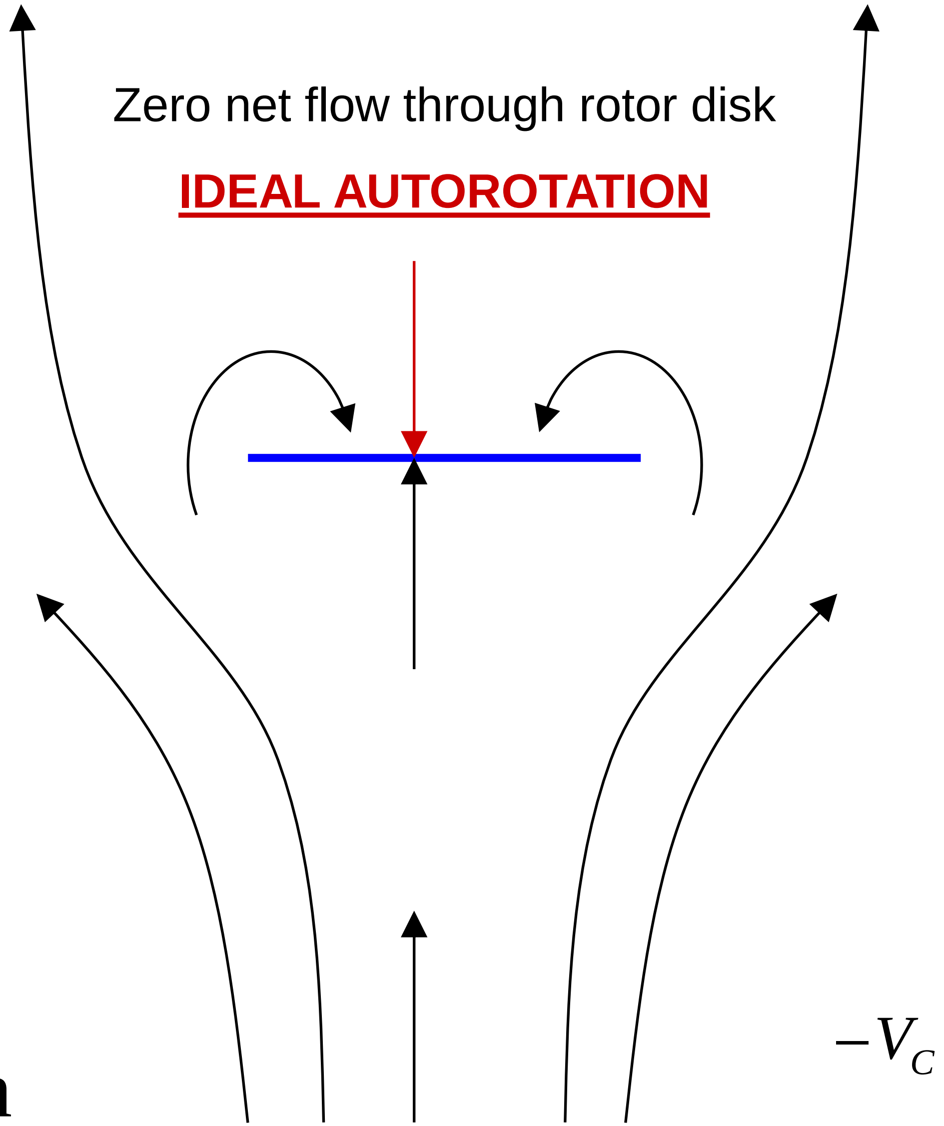
$$v > v_h$$

$$U \leq 0,$$

$$U \approx 0 \text{ ideal autorotation}$$

Zero net flow through rotor disk

IDEAL AUTOROTATION



TURBULENT WAKE STATE

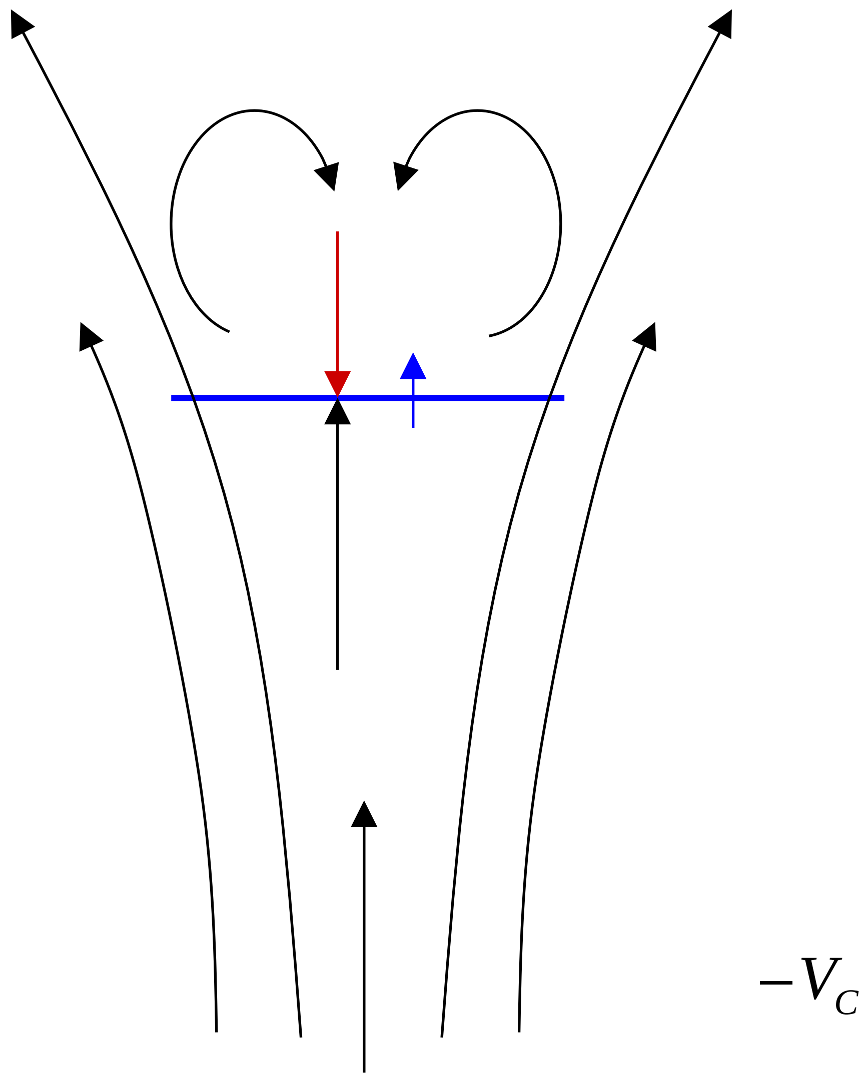
Rotor in HIGH DESCENT RATE

Momentum Theory does not apply as no effective stream tube exists.

$$-\frac{3}{2}v_h \geq V_V \geq -2v_h$$

$$v \geq v_h$$

$U < v$ *(and –ve in value)*



WINDMILL BRAKE STATE

Rotor in VERY HIGH DESCENT RATE

Momentum Theory applies as

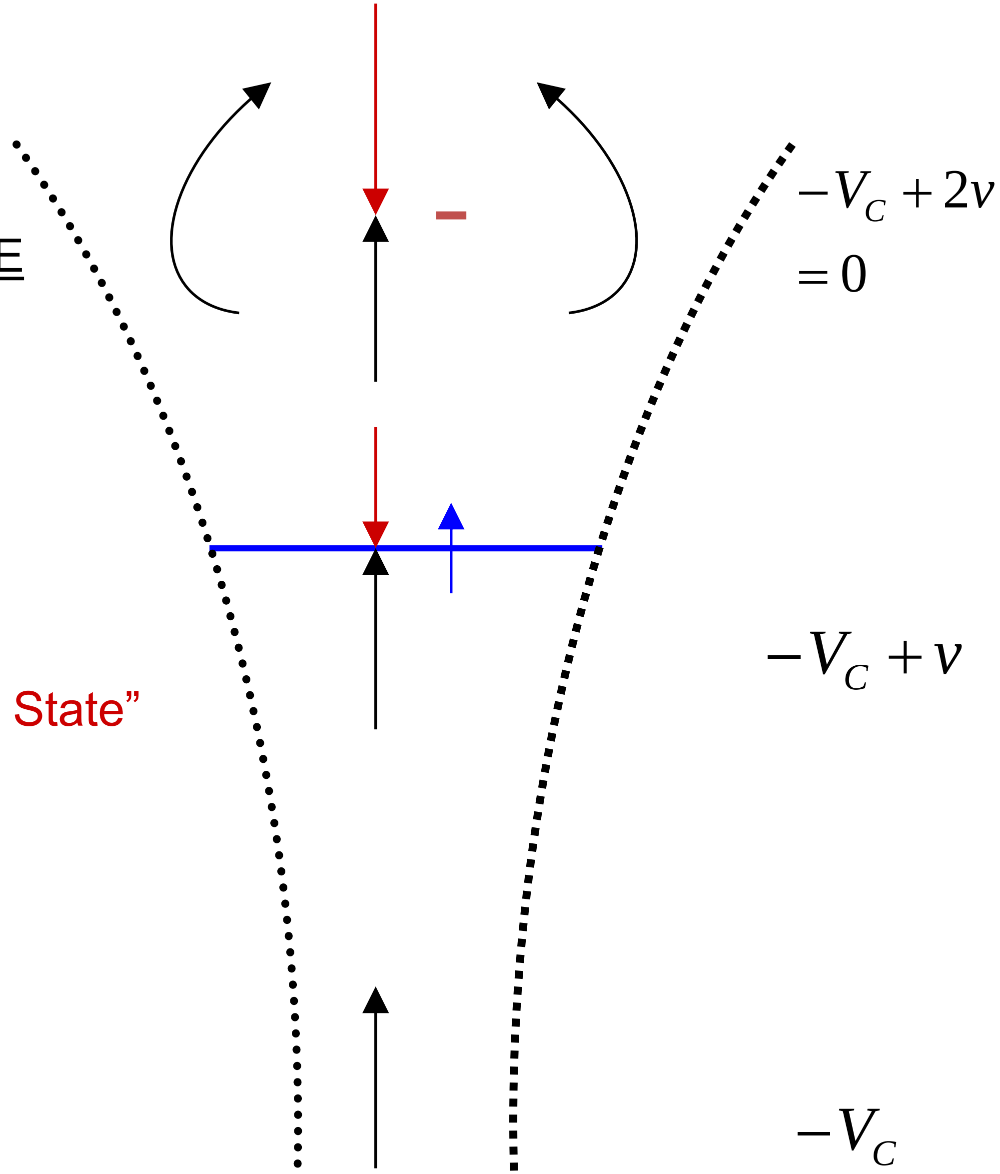
an effective stream tube exists.

This is analogous to “Normal Working State”

$$V_V \leq -2v_h$$

$$v \approx v_h$$

$U \leq v$ *(and –ve in value)*



WINDMILL BRAKE STATE

Rotor in EXTREME DESCENT RATE

Momentum Theory applies as

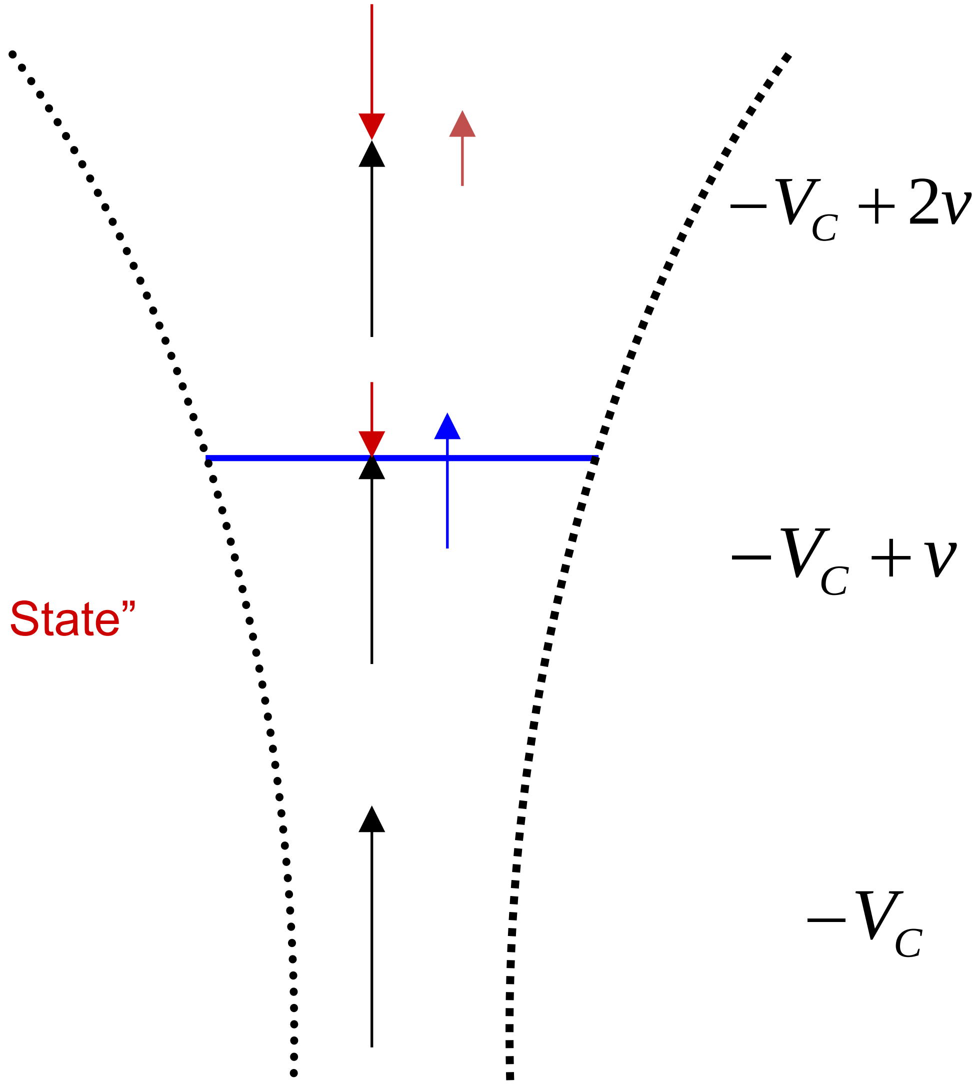
an effective stream tube exists.

This is analogous to “Normal Working State”

$$V_V << -2v_h$$

$$v < v_h$$

$$U \geq v$$



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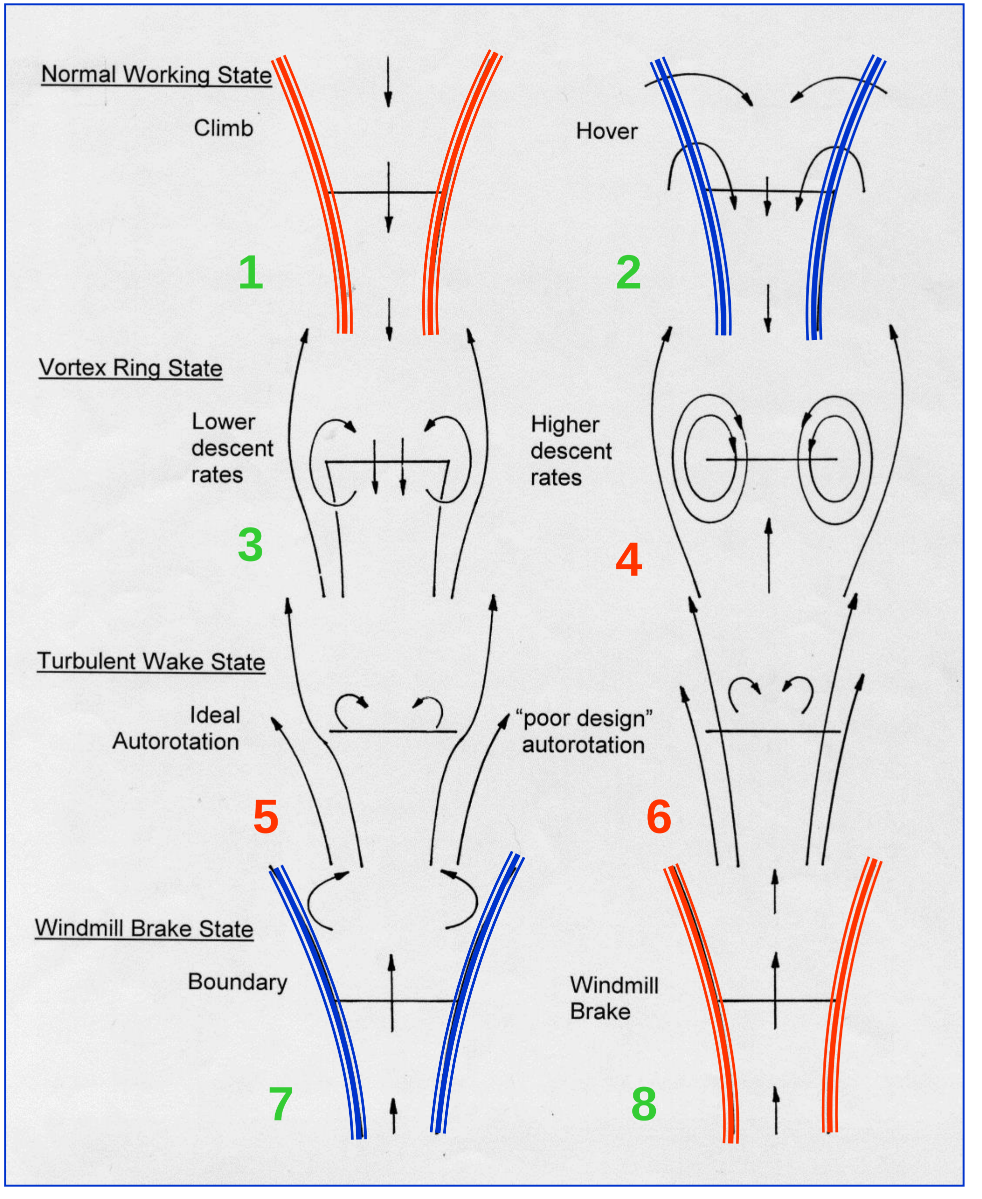
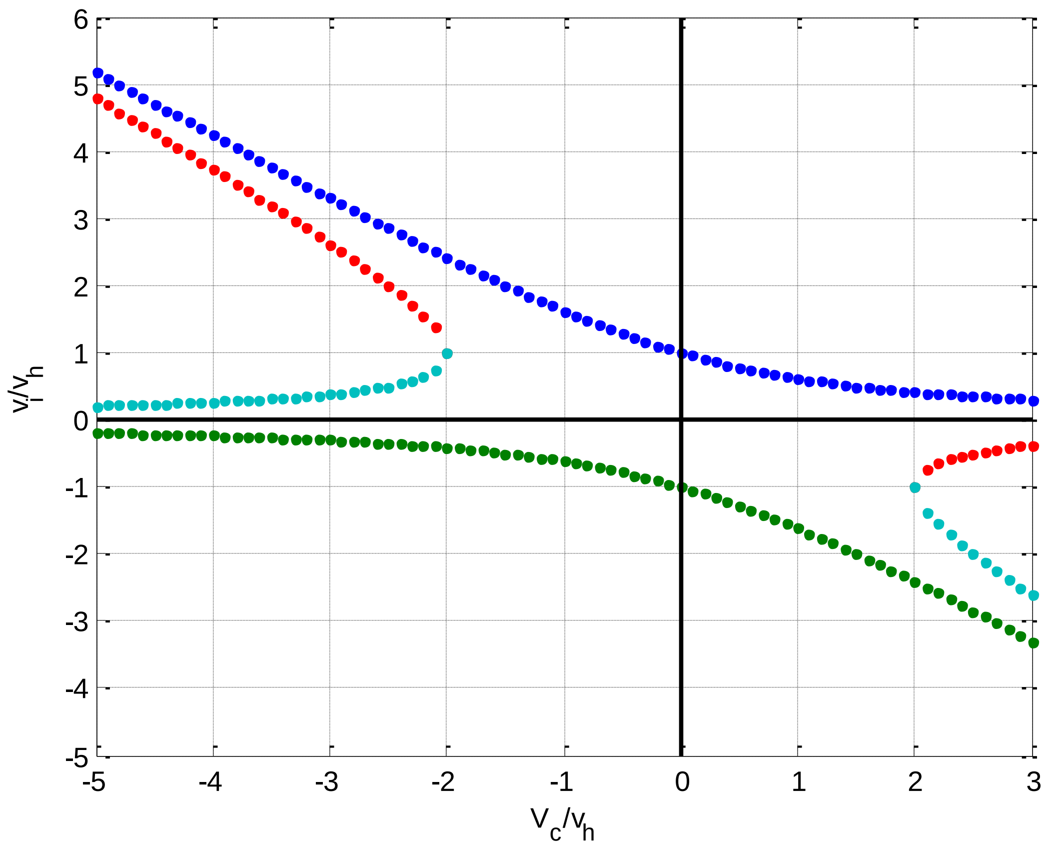


Question

- Starting from $T_{Hover} = T_{AxialFlight} = T$,
- i.e. $2\rho A v_h^2 = 2\rho A (V + v) v$
- Plot the variation of $\frac{v}{v_h}$ as a function of $\frac{V}{v_h}$

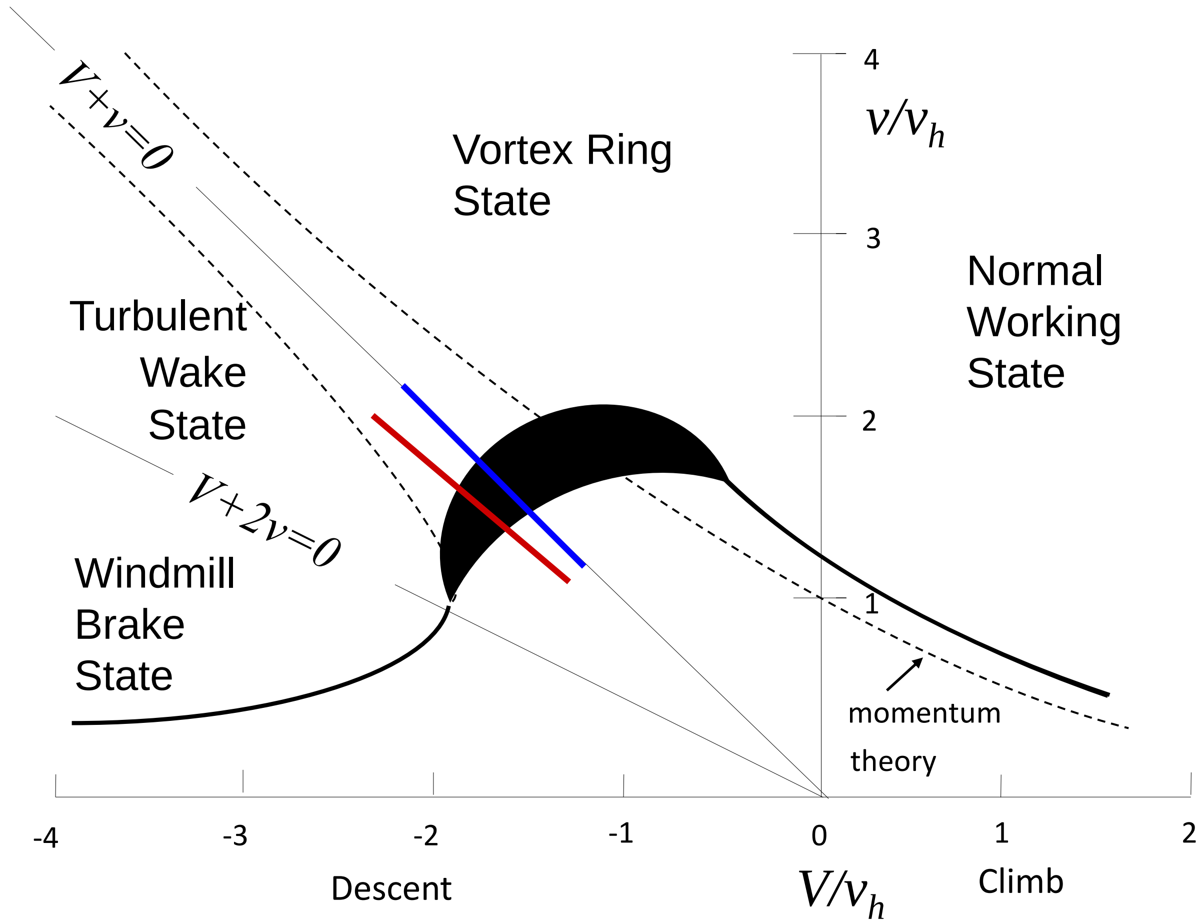
Answer

$$\frac{v_i}{v_h} = -\frac{V_c}{2v_h} \pm \sqrt{\left(\left(\frac{V_c}{2v_h}\right)^2 \pm 1\right)}$$



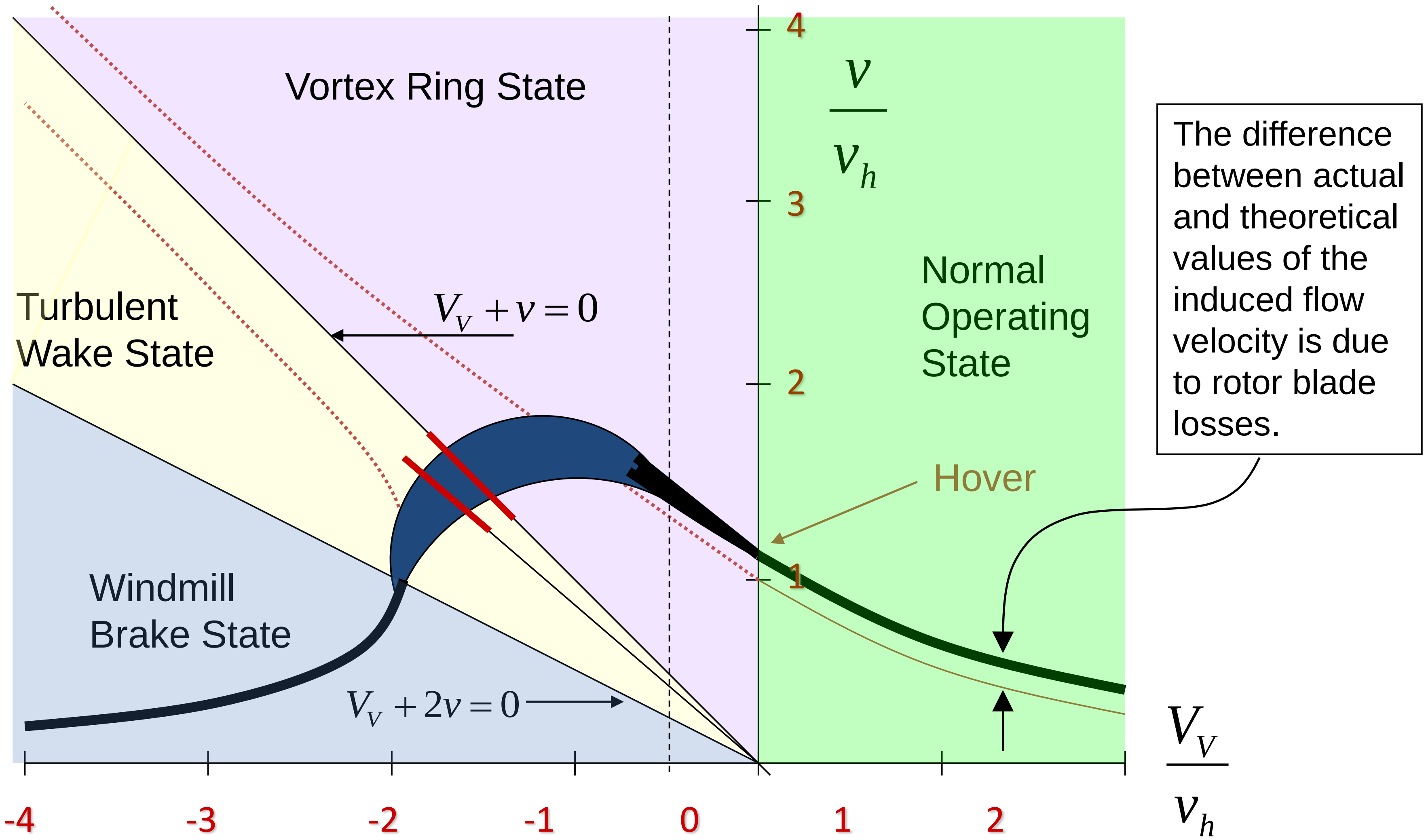
ALL THESE FLOW STATES

can now be summarised on one diagram, the Universal Induced Velocity Curve. The **dark area** is literally a "grey area" as it cannot be solved analytically and therefore comprises of empirical obtained by flight test.



The induced velocity (Y-axis) and the helicopter rotor's vertical velocity (X-axis) have been non-dimensionalised by the rotor induced velocity in the hover.

The Universal Induced Velocity Diagram



Remembering that $P = T(V + v)$, then at $(V + v) = 0, T \neq 0, P = 0$

HELICOPTER in Vortex Ring State

It is important to design for low autorotation rates