Aerodynamics 2- Rotorcraft Aerodynamics

Lecture 2

Rotorcraft History and Fundamentals of Vertical Flight

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Rotorcraft History - Fundamentals of Vertical Flight

On December 17th 1903, Orville Wright piloting the *Wright Flyer I*, made the world's first powered, sustained and controlled flight of an aircraft. This of course was a fixed wing aircraft, so when was the first successful flight of a rotary winged aircraft? The answer to that question is somewhat open to debate.

Long before the time of the Wright Brothers, attempts had been made to emulate bird flight and much energy (but never sufficient) was expended in this almost vertical direction. Even after the Wright Brothers when it was generally acknowledged that the power to weight ratio of the engines available at the time was far too low for direct vertical flight, the quest for vertical take-off and landing (VTOL) continued. So for another three decades pioneers attempted to fly in a purely vertical fashion. Whilst most of them achieved this, the flights were rarely out of "ground effects" and the aircraft control problems ensured that the flights were rarely repeatable.

By the mid-1920's the fixed wing aircraft (which had undergone substantial development, particularly during the First World War) was now a reliable form of air transport. It could operate safely in many environments and could even be landed on a ship but it still had one undesirable characteristic - if it flew too slowly it stalled. It occurred to some (in particular Juan de la Cierva) that if the lift producing wing could be less dependent on the aircraft's forward speed then the stall could be avoided. By replacing the fixed wing with a rotating wing, high levels of lift can still be maintained as the aircraft descends - thus the autogyro was born. Initially it appeared as a modified fixed wing aircraft, augmenting rather than replacing the fixed wings but as the level of confidence grew the fixed wings were progressively removed.

In the 1930's aircraft engine development was such that the power to weight ratio was sufficiently high (and rising) to make practical vertical flight viable. There were a number of eminent aeronautical engineers working on vertical flight at this time and the first successful closed circuit flight was made by the Breguet-Dorand coaxial helicopter in the latter part of 1936. The flight of 27 miles took just over an hour, flying at 500 ft. Shortly afterwards the Focke-Achgelis Fa 61 helicopter (with two side-by-side rotors) flew a 50 mile closed circuit at 8000 ft at speeds of 76 mph. Neither of these helicopters proceeded beyond the prototype stage but they were flown extensively and gave much needed confidence to the rotorcraft fraternity. In the USA Igor Sikorsky was working on a single main rotor design of helicopter, the VS-300 which had three tail rotors to provide the necessary control. After a number of tethered flights this helicopter flew freely in May 1940. The three tail rotor configuration was reduced to just one, for main rotor torque balance and helicopter control was achieved by cyclic pitch of the main rotor. This has remained the classic helicopter configuration, little changed even today. The VS-300 went into production and was (in the guise of the R-4) the first helicopter to be used by the services, initially by the US Navy and USAAF and subsequently by many other of the worlds' forces, (viz. the RAF Hoverfly I).

The coaxial helicopter has been successfully developed over the years (mainly by the Russians) and the two rotor design continues in the tandem rotor configuration (mainly Boeing) rather than side-by-side. Both these configurations benefit from a greater proportion of the power converted to lifting forces albeit at the cost of increased rotor complexity and weight. A combination of these two configurations can be seen in the syncropter (Mainly Kaman) which results in an aircraft with a particularly strong lifting capability. The anti-torque tail rotor of the conventional "penny-farthing" configuration has always been a source of embarrassment in the efficiency stakes of this otherwise simple design. Of the many attempts to provide a more efficient method of countering the main rotor torque, the use of the jet engine exhaust energy appears to be the most promising solution. This has been successfully demonstrated by the McDonnell Douglas NOTAR.

Aerodynamics of the Rotor in Axial Flight

For most cases of non-translational flight the helicopter will be in the hover. For climbing or descending it will be more efficient if the helicopter has some translational velocity. Never-the-less the helicopter does have the ability to operate in a number of axial flight conditions so an understanding of the associated flow states of the rotor is necessary. The helicopter's main rotor will need to operate in the more extreme of these flow states during a recovery from engine failure. The tail rotor is required to operate in all of theses flow states quite routinely.

It should be remembered that at all times the rotor is producing positive thrust and therefore a flow, v is induced through the rotor in the opposite sense to the thrust vector. If the flow through the rotor (due to the vertical velocity of the helicopter) V_v is considered to be positive in the climb condition then the total flow through the rotor $U = V_v + v$. There are basically four states of flow through the rotor:

NORMAL WORKING STATE - *from infinite climb to hover*

	Climb	Hover
$V_v =$	+ve (V_v is down)	0
$v =$	$< v_h$	v_h
$U =$	$> v$	v

This is the normal operating regime for a helicopter, the flow state is suitable for analysis using the momentum equations and it is therefore similar to the aeroplane propeller where static thrust is analogous to hover and forward flight to climb. Unfortunately this is where the similarity must end because for reasons that will be explained later, a rather different nomenclature has been adopted.

VORTEX RING STATE - *from hover* (ie. $V_v = 0$) *to* $-V_v = v$

	Slow Descent
$V_v =$	-ve (V_v is small to moderate)
$v =$	$> v_h$
$U =$	$< v$

Although not considered a "normal working state" the helicopter routinely operates at descent rates to $V_v = (-v_h/2)$ and the momentum theory still gives surprisingly good results. For $V_v \leq (-v_h/2)$ momentum theory is not valid and cannot be used.

TURBULENT WAKE STATE - *from* $-V_v = v$ *to* $-V_v = 2v$

	Moderate Descent
$V_v =$	-ve (V_v is moderate to large)
$v =$	$> \boldsymbol{v_h}$
$U =$	≤ 0

Still a very turbulent flow state but there is much less recirculation through the rotor than in the "vortex ring state". Autorotation exists when $V_v + v \leq 0$ (ideal autorotation when $V_v + v = 0$). The momentum theory is not valid and cannot be used

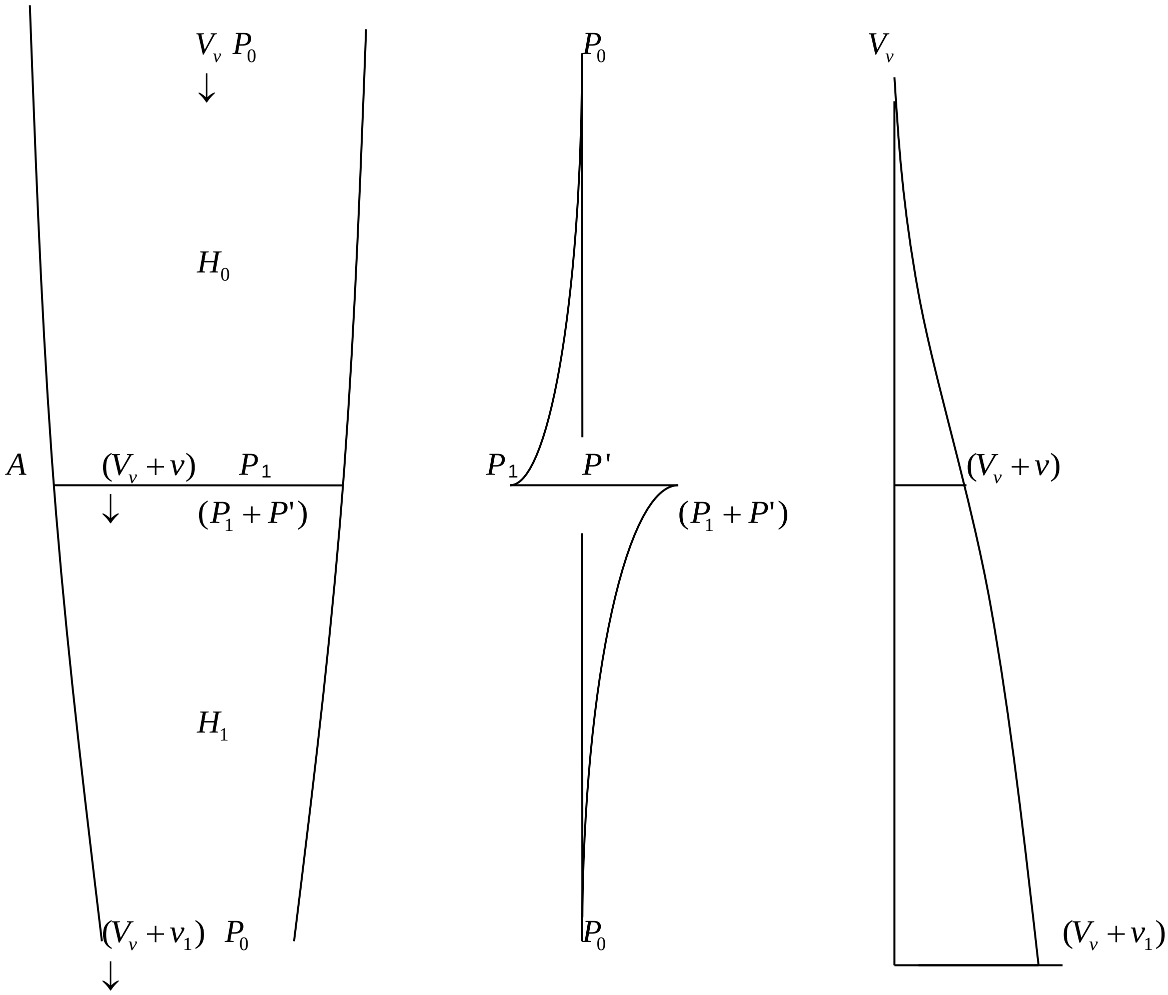
WINDMILL BRAKE STATE - *from* $-V_v = 2v$ *to* $-V_v = \infty$

	Rapid Descent
$V_v =$	-ve (V_v is large)
$v =$	$\leq v_h$
$U =$	>> 0 (up)

Now the flow is a definite slipstream as it is in the "normal working state" but the flow is everywhere upwards, (opposite to the rotor climb). The momentum theory is again valid and yields good results.

Momentum Analysis - (for rotor in Normal Operating State)

The helicopter rotor can be considered as an actuator disc with an infinite number of blades operating in an ideal fluid. The flow is considered non-rotational and therefore swirl can be neglected. The actuator disc has an area A and it can support a pressure differential P'.



$$H_0 = P_0 + \tfrac{1}{2}\rho V^2 = P_1 + \tfrac{1}{2}\rho (V+v)^2$$

$$H_1 = P_0 + \tfrac{1}{2}\rho (V+v_1)^2 = P_1 + P' + \tfrac{1}{2}\rho (V+v)^2$$

$$\frac{T}{A} = \rho (V+v) v_1 = P' = \rho v_1 (V + \frac{v_1}{2})$$

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

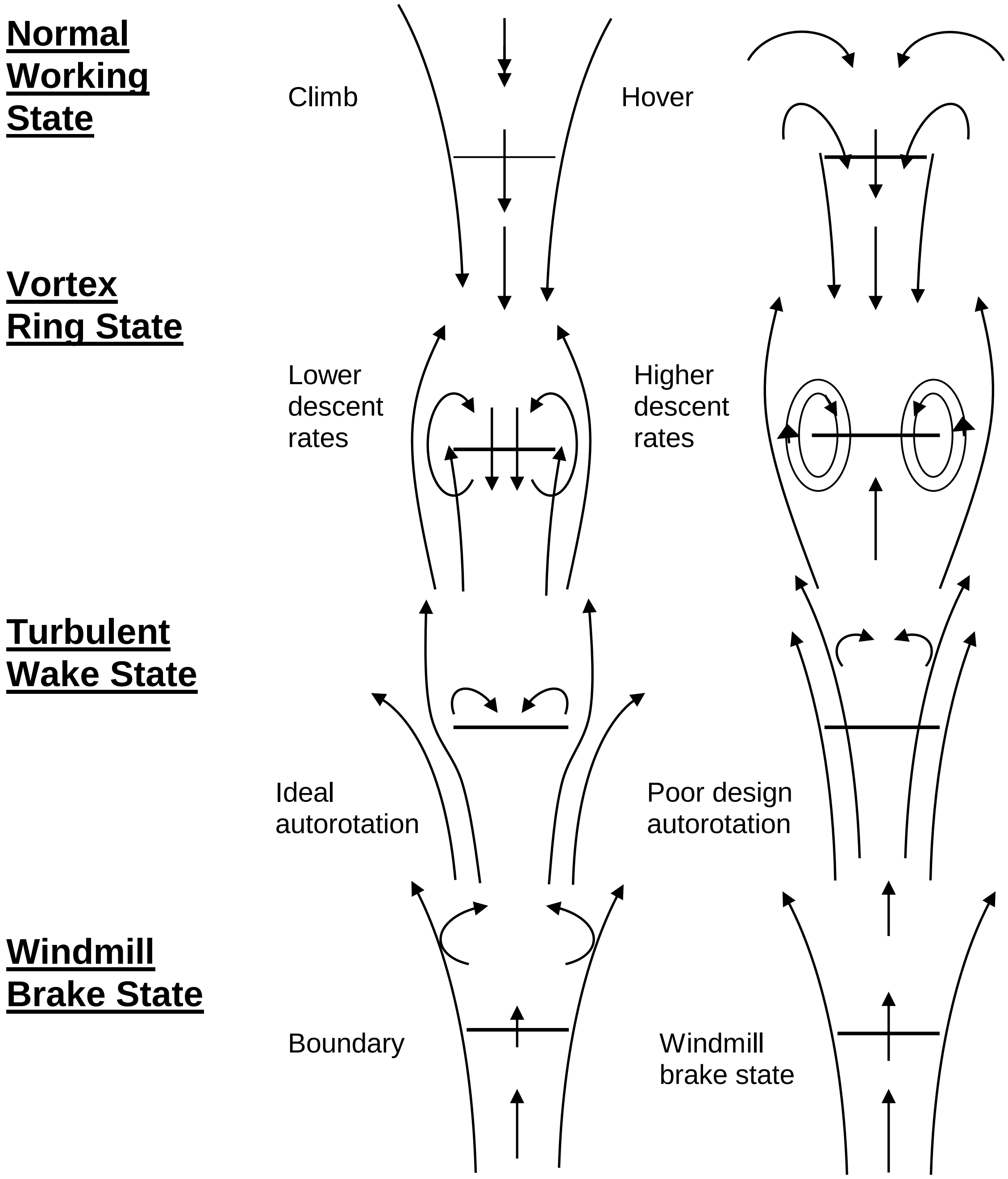
$$Thrust, T = 2\rho A (V+v) v$$

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

Visualisation of the Four Axial Flow States

The four rotor working states are best visualised as shown below:

It should be noted that the two extreme cases, climb and fast descent have almost identical streamlines albeit of opposite sign. These well defined stream tubes are therefore suited to analysis by momentum consideration. The adjacent states of the aforementioned are also very similar, the entry into the “windmill brake state” had an induced velocity in the order of v_h and the downstream wake stagnates in a similar manner to the inflow for the hover.



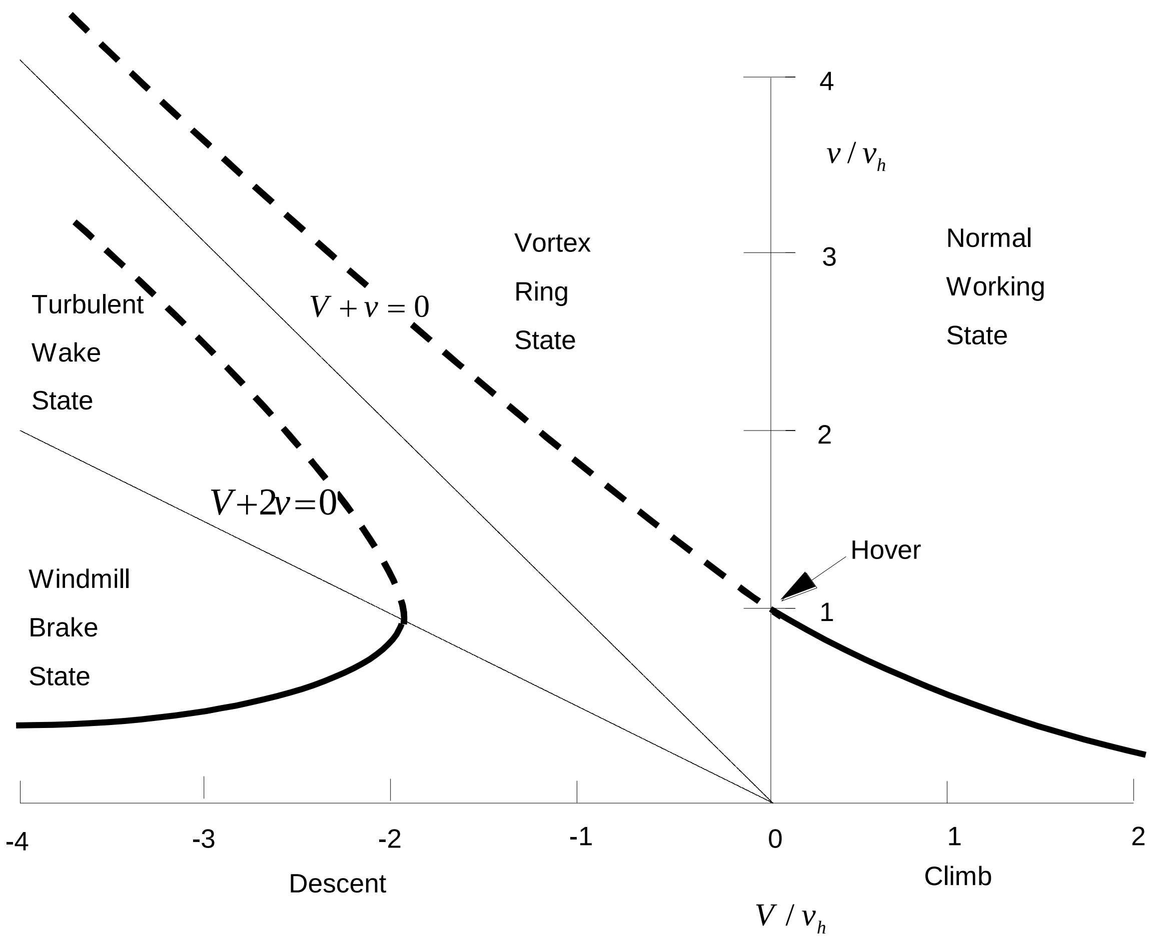
A graph showing the validity of the momentum theory of analysis for the rotor flow states is given below. The Induced velocity v and the climb velocity V_v have been non-dimensionalised by dividing by the induced velocity in the hover v_h.

The continuous lines indicate the relationship between induced velocity at the rotor and the climb / descent velocity where the momentum equations are valid. The dotted lines are projections of these lines into the vortex ring and turbulent wake state where the momentum equations are not valid.

It can be seen that the line at 45^o through the origin is the line along which <u>ideal autorotation</u> can occur since $V+v=0$ and therefore zero power condition results.

[*remembering that* $P=T(V+v)$ *and since* $V+v=0$, *then* $P=0$]

Whilst $P=0$, $T\neq 0$ as $TV=Tv=Wv$ where W is the weight of the helicopter for a steady state autorotative descent. This is however for ideal autorotation and in reality that cannot exist. Some power is required to keep the main rotor turning, overcome the transmission losses and drive the tail rotor. The tail rotor is intrinsically linked to the main rotor but will not be required to produce thrust for that rotor while it autorotates. Thus the line for actual autorotation will be further into the Turbulent Wake state at a lower angle of say 42^o, where $P=T(V+v)+P_0=0$



In general (and this very much depends upon rotor diameter and helicopter weight), helicopters settle down to an autorotational descent rates such that $V/v_h \approx -1.7$

Now in a steady autorotative descent, $T = W =$ thrust in the hover

and therefore $T = 2\rho A v_h^2$

The rotor has no net flow through it so it can be likened to a solid disc of diameter A.

and it's Flat Plate Drag $D = 1/2\,\rho V^2 A C_D$

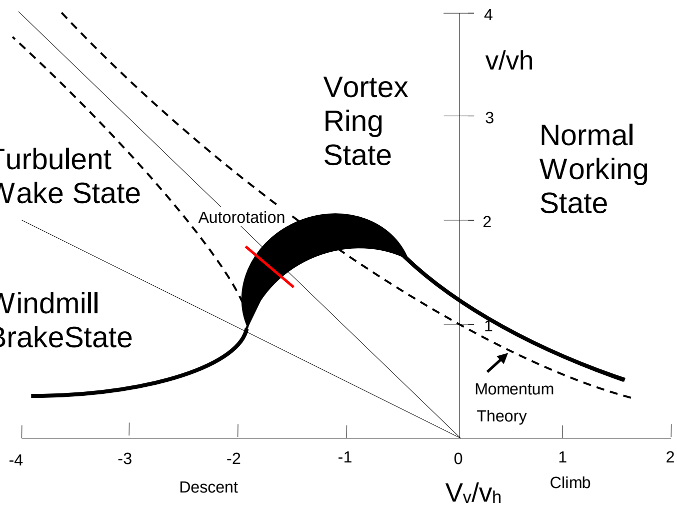
Equating the Thrust and Drag equations $T = D$ gives:

$$2\rho A v_h^2 = 1/2\,\rho V^2 A C_D$$
$$C_D = \frac{4}{(V/v_h)^2}$$

For $V/v_h = -1.7$, $C_D = 1.38$ which is the effective drag coefficient of a parachute.

It is obvious that flight in the region of autorotative descent is too important to be left without some knowledge of the induced velocity values. Because these cannot be determined by momentum considerations, other methods have had to be used. Flight testing in these areas allowed the rotor power and rotor thrust to be measured at various axial velocities.

From the values of thrust and power coefficients (and an estimate of C_{P_0}) the induced velocity was determined. These values have been used to complete the induced velocity curve across the range of flow states. This is known as the "Universal Induced Velocity Curve". This semi-empirical chart is used to predict helicopter autorotational performance.



The Universal Induced Velocilty Curve

In the hover and in the climb the measured induced velocity is higher than the momentum theory result by a small but relatively constant factor. This is because the momentum takes no account for losses due to a non-uniform inflow and tip effects. These losses must be kept to a minimum if the primary role of the helicopter is for hover or axial flight. A "Figure of Merit" is used to gauge the efficiency of the hovering rotor and this will be discussed in the next lecture.