Chapter 2

# Helicopter Flight Physics

Constantin Rotaru and Michael Todorov

Additional information is available at the end of the chapter

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**Abstract**

This chapter is dedicated to present the principles that constitute the fundamentals of helicopter flight physics, starting from the basics of the main rotor aerodynamics and of the component parts related to flight control. The chapter opens with a short history of helicopter development, taking the date of 13th November 1907 for a reference point; this is the date when the first helicopter flight occurred, having the French man, Paul Cornu, for a pilot. The main constructive solutions for helicopters are presented and the basic equations of fluid mechanics are applied on a helicopter model with one main rotor and tail rotor. Helicopter hovering, vertical flight, and forward flight are approached, too, one by one. Furthermore, the ground effect, autorotation, stability, and helicopter control are focused on. At the end of the chapter, the main factors that determine the helicopter performances are mentioned.

**Keywords:** helicopter aerodynamics, induced velocity, autorotation, ground effect, hover

## 1. Introduction

The helicopter belongs to the flight machine category with the highest operational efficiency because it does not need special take-off and landing grounds with expensive utilities and logistics equipment. For the short and medium range, the flight efficiency of helicopters is comparable with those of the airplanes. It is able to hover, fly sideward, backward, forward, and perform other desirable maneuvers in civilian field like sea and mountain rescue, police surveillance, and firefighting; or in military missions such as battlefield surveillance, troop transport, assault, and antitank operations. So far with the help of helicopters, lives of over a million of people were saved. In the last years, the results obtained in the scientific research of many aeronautical disciplines has allowed for large increase in the flight dynamics, control, navigation, and lift capabilities of helicopters.

The aerodynamic limitations imposed by the main rotor were understood better and overcome gradually so, the present helicopters are able to fly at about 370 km/h. The continued advance in the computer-aided design, manufacturing, and lightweight materials have permitted new approaches in the helicopter configuration concepts and design. The helicopter lift force is provided by the main rotor with the blades that spin about the shaft and all the flight maneuvers under the pilot's full control suppose a significant mechanical and aerodynamic complexity.

The word "helicopter" comes from two Greek words, "helliko" (spiral) and "pteron" (wing). The idea of vertical flight could be localized in time, in the years of about 400 BC, when was built so called "Chinese top," consisted of feathers at the end of a stick which was spun between the hands to generate lift. In 1483, Leonardo da Vinci proposed a flight device, which comprised a helical surface formed out of iron wire. According to the historical sources, in about 1754, Mikhail Lomonosov of Russia had built a coaxial rotor, modeled after the Chinese top, but powered by a spring device, which flew freely.

A short list of the most important achievements in the historical evolution of helicopters is the following:

1843: Sir George Cayley (considered the inventor of the airplane) published a paper, where he gives some scientific details about the vertical flight of the aircraft;

1860: Ponton d"Amecourt of France built a number of small steam-powered helicopter models;

1874: Wilheim von Achenbach of Germany built a single rotor model and he had the idea to create a sideward thrusting tail rotor in order to counteract the main rotor torque reaction;

1880: Thomas Alva Edison tested several rotor configurations powered by an electric motor;

Four years after Orville Wright first successful powered flight, which took place in December 17, 1903, a French, named Paul Cornu constructed a helicopter and *flew for the first time in the world in November 13, 1907*;

1907: the French brothers Louis and Jaques Breguet built a helicopter (quad rotor, in the form of a horizontal cross) powered by a 40-hp. engine. This helicopter did not fly completely free due to its lack of stability;

1909: Igor Ivanovitch Sikorsky built a nonpiloted coaxial helicopter prototype;

1912: Boris Yuriev tried to build a helicopter with a single main rotor and tail rotor configuration. He proposed the concept of cyclic pitch for rotor control;

1914: the Danish Jen C. Ellehammer designed a helicopter with coaxial rotors. The aircraft made several short hops but never made a properly flight;

1917: Stephan Petroczy (Austrian) build and flew a coaxial rotor helicopter;

1919: Henry Berliner (USA) built a counter-rotating coaxial helicopter;

1920: Raul Pescara (Argentina) built a coaxial helicopter;

1922: Georges des Bothezat (USA) designed and built a helicopter for the USA army. He was the first specialist who described the helicopter autorotation;

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1939: Igor Ivanovitch Sikorsky built the helicopter VS-300 which flew in May 13, 1940. He could be considered the most important person in the helicopter design.

### 1.1. Helicopter configurations

The helicopter is a complex aircraft that obtains both lift and thrust from blades rotating about a vertical axis. The term “rotary wing” is often used to distinguish the helicopter from airplane, which is a “fixed wing” aircraft. The helicopter can have one or more engines, and it uses gear boxes connected to the engines by rotating shafts to transfer the power from engines to the rotors (**Figure 1**).

The most common helicopter configuration consists of one main rotor as well as a tail rotor to the rear of the fuselage (**Figure 2a**). A tandem rotor helicopter has two main rotors; one at the front of the fuselage and one at the back (**Figure 2b**). This type of configuration does not need a tail rotor because the main rotors are counter rotating. It was proposed by the Serbian man Dragoljub Ivanovich in 1953.

A variant of the tandem is the coaxial rotor helicopter (**Figure 3a**) which has the same principle of operation, but the two main rotors are mounted one above the other on coaxial rotor shafts. This constructive solution was developed by Nicolai Ilich Kamov. Another helicopter type is the synchropter, which use intermeshing blades (**Figure 3b**). This type of helicopter was proposed by Charles Kaman.

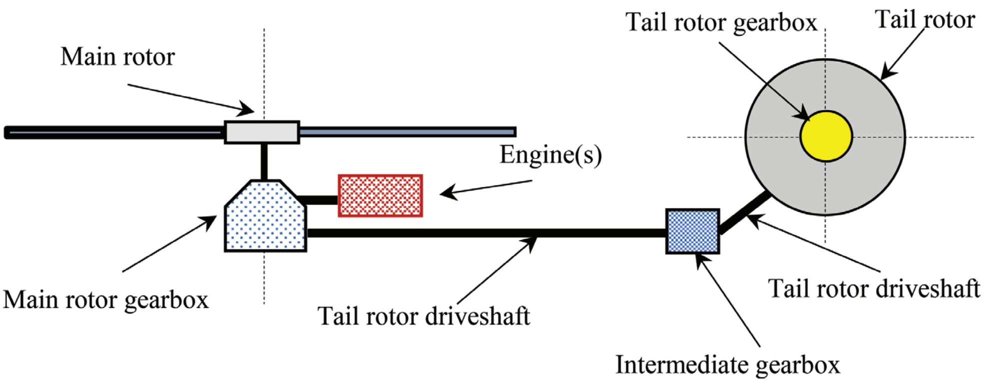


**Figure 1.** Typical helicopter drive train.


**Figure 2.** The single main rotor (a) and the tandem rotor helicopter (b).


**Figure 3.** The coaxial rotors (a) and the intermeshing blades (b).

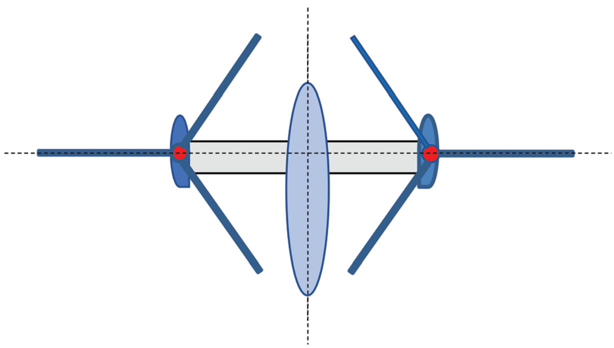

**Figure 4.** The side by side rotors.

If the two rotors are mounted either side of the fuselage, on pylons or wing tips, the configuration is referred to as side by side (**Figure 4**).

Another aircraft type that should be mentioned is the autogiro (invented by Huan de la Cievra), which is a hybrid between a helicopter and a fixed wing airplane. It uses a propeller for the forward propulsion and has freely spinning nonpowered main rotor that provides lift.

## 2. Basics of helicopter aerodynamics

The basic flight regimes of helicopter include hover, climb, descent, and forward flight, and the analysis and study of these flight regimes can be approached by the actuator disk theory, where an infinite number of zero thickness blades support the thrust force generated by the rotation of the blades [1]. The air is assumed to be incompressible and the flow remains in the same direction (one-dimensional), which for most flight conditions is appropriate. The helicopter main rotor generates a vertical force in opposition to the helicopter's weight and a horizontal propulsive force for forward flight. Also, the main and tail rotors generate the forces and moments to control the attitude and position of the helicopter in three-dimensional space.

### 2.1. Hovering flight

The cross sections in **Figure 5** denote: the plane far upstream of the rotor, where in the hovering case the air velocity is null (section 0–0); the planes just above and below the rotor

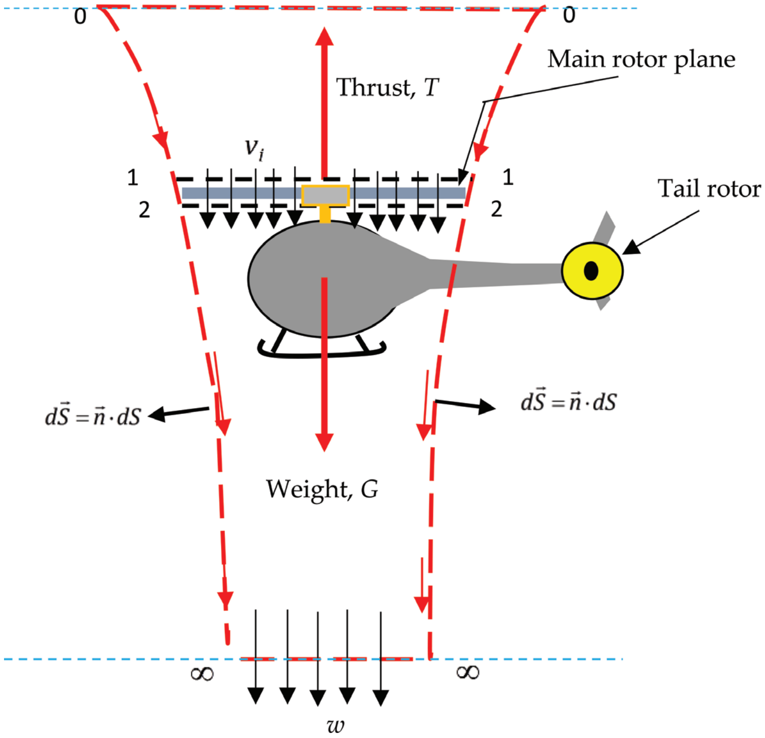


**Figure 5.** The helicopter in hovering flight.

disk (sections 1–1, and 2–2); the far wake section, denoted by ∞. At the plane of rotor, the velocity through the rotor disk is $v_i$ (named the induced velocity) and in the far wake the air velocity is $w$. For a control volume surrounding the rotor and its wake, as shown in **Figure 5** and $d\vec{S} = \vec{n} \cdot dS$ the unit normal area vector (the unit normal vector $\vec{n}$ is oriented outward the control volume), according to the Reynolds Transport Theorem, for any extensive parameter $B$, where $B = b \cdot m$, the following equation is valid

$$\left(\frac{dB}{dt}\right)_{system} = \frac{\partial}{\partial t} \iiint\limits_{\substack{control\\volume}} \rho b dV + \iint\limits_{\substack{control\\surface}} (\rho b)\vec{V} \cdot d\vec{S} \tag{1}$$

where $\vec{V}$ is the local velocity, $m$ is the mass of fluid, and $\rho$ is the fluid density. For a steady flow, the above equation becomes

$$\left(\frac{dB}{dt}\right)_{system} = \iint\limits_{\substack{control\\surface}} (\rho b)\vec{V} \cdot d\vec{S} \tag{2}$$

**The conservation of mass** (this case corresponds to $B=m$ and $b=1$)

$$\left(\frac{dm}{dt}\right)_{system} = \iint\limits_{\substack{control \\ surface}} (\rho)\vec{V} \cdot d\vec{S} \tag{3}$$

This equation requires the condition that the total amount of mass entering a control volume equals the total amount of mass leaving it. For steady-flow processes, we are not interested in the amount m of mass that flows in or out the control volume, but we are interested in amount of mass flowing per unit time, that is the mass flow rate, $\dot{m}$, well the conservation of fluid mass applied to this finite control volume can be rewritten as

$$-\iint\limits_{surface2} \rho v_i dS + \iint\limits_{surface\infty} \rho w dS = 0 \tag{4}$$

Therefore,

$$\rho v_i A = \rho w A_\infty \tag{5}$$

**The conservation of fluid momentum** (this case corresponds to $B = m\vec{V}$ and $b = \vec{V}$)

$$\left(\frac{dm\,\vec{V}}{dt}\right)_{system} = \iint\limits_{\substack{control \\ surface}} \left(\rho\vec{V}\right)\vec{V} \cdot d\vec{S} \tag{6}$$

The principle of conservation of fluid momentum gives the relationship between the rotor thrust and the time rate of change of fluid momentum out of the control volume. The left part of Eq. (6) represent the sum of all forces that operate upon the control volume, namely the helicopter rotor thrust force, T. In projection on rotational axis, Eq. (6) becomes

$$T = w \iint\limits_{surface\infty} (\rho w) dS = w\dot{m} \tag{7}$$

where $\dot{m}$ is the mass flow rate in the control volume.

**The conservation of energy** (in this case $B = E = \frac{1}{2}mV^2$ and $b = \frac{1}{2}V^2$)

$$\left(\frac{dE}{dt}\right)_{sistem} = \iint\limits_{\substack{control \\ surface}} \left(\rho\frac{1}{2}V^2\right)\vec{V} \cdot d\vec{S} \tag{8}$$

The work done on the helicopter rotor is equal to the gain in energy of the fluid per unit time, and $dE/dt$ represents the power consumed by the rotor, being equal to $T \cdot v_i$, therefore,

$$T \cdot v_i = \iint\limits_{\substack{control \\ surface}} \left(\rho \frac{1}{2} V^2\right) \vec{V} \cdot d\vec{S} = \frac{1}{2} w^2 \dot{m} \tag{9}$$

Taking into account that $T = \dot{m}w$, we have $\dot{m}\, w\, v_i = \frac{1}{2} w^2 \dot{m}$ or $v_i = \frac{1}{2} w$.

From the equation of continuity $\rho v_i A = \rho w A_\infty$, it follows that $A_\infty = \frac{1}{2} A$ and obviously, $r_\infty = \frac{R}{\sqrt{2}}$ therefore, the ratio of the rotor to the radius of the wake is $R/r_\infty = \sqrt{2}$.

Replacing the velocity $w$ in the vena contracta (section $\infty$) in the expression of thrust force $T$, it follows that

$$T = \dot{m}w = \dot{m}(2v_i) = \rho A v_i (2v_i) = 2\rho A v_i^2 \tag{10}$$

The induced velocity at the plane of the rotor disk is $v_{hover}$,

$$v_h = v_i = \sqrt{\frac{T}{A} \frac{1}{2\rho}} \tag{11}$$

This expression shows that induced velocity is dependent explicitly on the disk loading $T/A$, which is an important parameter in the helicopter design.

The power required to hover is the product between thrust $T$ and induced velocity $v_i$,

$$P = T \cdot v_i = T\sqrt{\frac{T}{A} \frac{1}{2\rho}} = \frac{T^{\frac{3}{2}}}{\sqrt{2\rho A}} \tag{12}$$

This power, called the ideal power, forms the majority of the power consumed in hover, which is itself a high power-consuming helicopter flight regime.

In assessing rotor performance and compare calculations for different rotors, nondimensional quantities are useful. The induced velocity is normalized using the rotor tip speed, $R\Omega$, where $R$ is the rotor radius and $\Omega$ is the angular velocity,

$$\lambda_h = \frac{v_i}{R\Omega} \tag{13}$$

The parameter $\lambda_h$ is called the induced inflow ratio in hover.

The thrust force is also normalized like the lift for the fixed-wing, that is, the product of a pressure and an area, where the pressure is the dynamic pressure, considered at the rotor blade tips and the area is the total disk area, $A = \pi R^2$, so, the thrust coefficient is defined by

$$C_T = \frac{T}{\frac{1}{2}\rho(R\Omega)^2 \cdot A} \tag{14}$$

The inclusion on the half in the denominator is consistent with the lift coefficient definition for a fixed-wing aircraft. The rotor power, $C_P$, and rotor torque, $C_Q$, are defined as

$$C_P = \frac{P}{\frac{1}{2}\rho(R\Omega)^3 \cdot A}; \quad C_Q = \frac{P}{\frac{1}{2}\rho(R\Omega)^2 \cdot R \cdot A} \tag{15}$$

Taking into account that power is related to torque by $P = \Omega \cdot Q$, then numerically $C_P = C_Q$.

Starting from the definition of the induced inflow ratio in hover, $\lambda_h$, it follows that

$\lambda_h = \frac{v_i}{R\Omega} = \frac{1}{R\Omega}\sqrt{\frac{T}{2\rho A}} = \sqrt{\frac{T}{4 \cdot \frac{1}{2}\rho A(R\Omega)^2}} = \frac{1}{2}\sqrt{C_T}$, therefore $C_T = 4\lambda_h^2$.

The rotor power coefficient can be represented as

$$C_P = \frac{T \cdot v_i}{\frac{1}{2}\rho(R\Omega)^3 \cdot A} = \frac{T}{\frac{1}{2}\rho(R\Omega)^2 \cdot A}\frac{v_i}{(R\Omega)} = C_T \cdot \lambda_i, \text{ or } C_P = \frac{1}{2}C_T^{\frac{3}{2}} \tag{16}$$

## 2.2. Vertical climb

Considering the helicopter in climb, one can see that the flow enters the stream tube far upstream of the rotor and then passes through the rotor itself, finally passing away from the rotor forming the wake (**Figure 6**). When the helicopter leaves the hovering condition and moves in a vertical direction, the flow remains symmetrical about the thrust force line, which is normal to the rotor disk. The flow becomes very complex in a medium descent rate condition, but in climb, the mathematical approach is close to that used in the hover conditions.

The air enters the stream tube with velocity $V_c$ and then acquires an additional velocity $v_i$ as it passes through the helicopter rotor disk, and finally, it forms the wake with a velocity $V_c + v_i$. Applying the principles of conservation for mass, momentum, and energy like in the hover we get:

$$\dot{m} = \rho A(V_C + v_i); \quad T = \dot{m}w; \quad w = 2v_i \tag{17}$$

Therefore, $T = \dot{m}w = \rho A(V_C + v_i) \cdot 2v_i$ and dividing by $2\rho A$ it follows that

$$\frac{T}{2\rho A} = (V_C + v_i)v_i = V_C \cdot v_i + v_i^2 \tag{18}$$

The left part of the above equation represents the square of induced velocity in hover, $v_h^2$, and replacing it, we get

$$v_h^2 = V_C \cdot v_i + v_i^2 \quad \text{or} \quad \left(\frac{v_i}{v_h}\right)^2 + \frac{V_C}{v_h} \cdot \left(\frac{v_i}{v_h}\right) - 1 = 0 \tag{19}$$

The ratio $v_i/v_h$ must always be positive in the climb, so the valid solution is

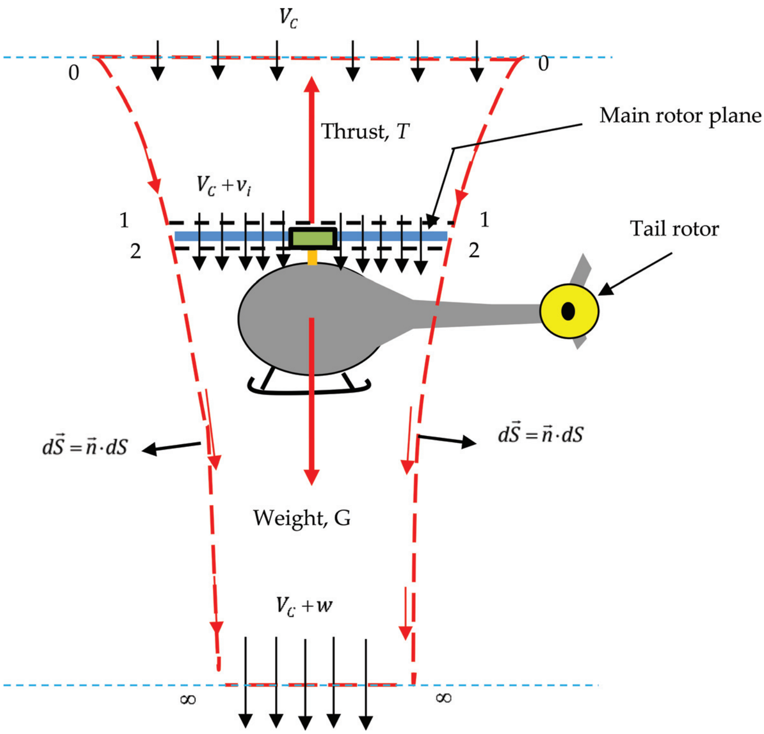


**Figure 6.** The axial climbing flight.

$$\frac{v_i}{v_h} = -\frac{1}{2}\frac{V_C}{v_h} + \sqrt{\frac{1}{4}\left(\frac{V_C}{v_h}\right)^2 + 1} \tag{20}$$

The power consumed is given by the product of the thrust and the total velocity through the rotor disk, that is

$$P = T(V_c + v_i) = T \cdot V_C + T \cdot v_i = P_{c\,\lim b} + P_i \tag{21}$$

## 2.3. Vertical descent

In the vertical descent, the air enters the stream tube from below the rotor with velocity $V_D$ and passes through the rotor disk with the velocity $V_D - v_i$, the wake being formed with velocity $V_D - w$, as it is shown in **Figure 7**. The mass flow rate in vertical descent is $\dot{m} = \rho A(V_D + v_i)$, where $V_D$ is negative, and the conservation of momentum gives the thrust force

$$T = \iint\limits_{\substack{control\\surface}} \left(\rho\vec{V}\right)\vec{V} \cdot d\vec{S} = -\dot{m} \cdot w \tag{22}$$

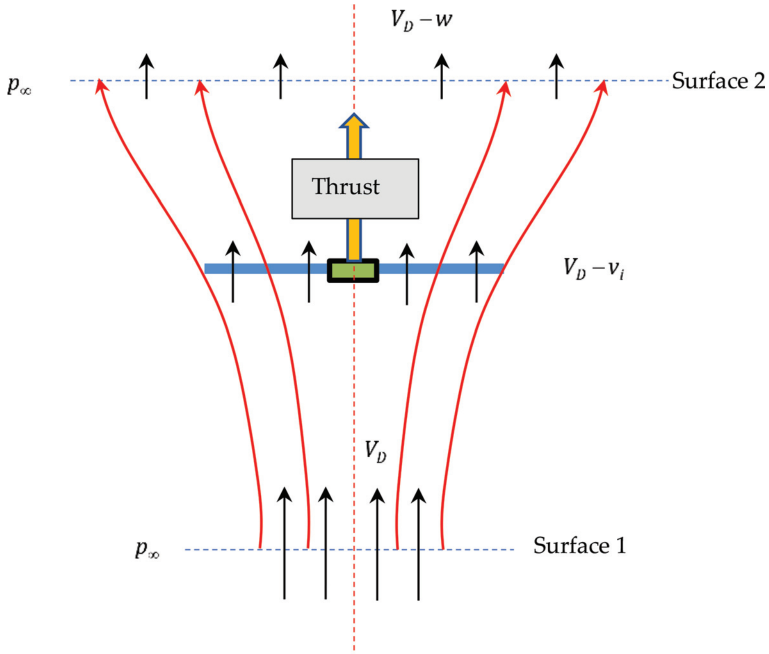


**Figure 7.** The stream tube in descent.

Even if the sign of thrust is negative, that does not mean that the thrust is negative, because the assumed sign convention consists of positive velocity $w$, in down direction. According to the conservation energy principle, it follows that

$$T \cdot (V_D - v_i) = -\frac{1}{2}\dot{m}w(2V_D - w) \tag{23}$$

Replacing the expression of thrust $T$, namely $T = -\dot{m}w$, in the above equation, we have

$$-\dot{m}w(V_D - v_i) = -\frac{1}{2}\dot{m}w(2V_D - w) \tag{24}$$

therefore, $v_i = \frac{w}{2}$.

Similarly, to climb case, having the expression of the mass flow rate $\dot{m} = \rho A(V_D + v_i)$, where velocity $V_D$ is negative and $v_i$ is positive, we can write

$$T = -\dot{m}w = -\rho A(V_D + v_i) \cdot 2v_i = -2\rho A(V_D + v_i)v_i \tag{25}$$

so

$$\frac{T}{2\rho A} = -V_D \cdot v_i - v_i^2 \tag{26}$$

Dividing by $v_h^2 = \frac{T}{2\rho A}$ the above equation becomes

$$\left(\frac{v_i}{v_h}\right)^2 + \frac{V_D}{v_h}\left(\frac{v_i}{v_h}\right) + 1 = 0 \tag{27}$$

with the solutions

$$\frac{v_i}{v_h} = -\frac{1}{2}\frac{V_D}{v_h} \pm \sqrt{\frac{1}{4}\left(\frac{V_D}{v_h}\right)^2 - 1} \tag{28}$$

In order to have real solutions, the following condition must be accomplished

$$\frac{1}{4}\left(\frac{V_D}{v_h}\right)^2 - 1 \geq 0 \tag{29}$$

That means, $|V_D| > 2v_h$. The valid solution is

$$\frac{v_i}{v_h} = -\frac{1}{2}\frac{V_D}{v_h} - \sqrt{\frac{1}{4}\left(\frac{V_D}{v_h}\right)^2 - 1} \tag{30}$$

In the region of flight that corresponds to $-2 \leq V_D/v_h \leq 0$, the control volume cannot be defined and the velocity curve can be defined experimentally. An approximation of the velocity in this region, called vortex ring state, could be [1]

$$\frac{v_i}{v_h} = k + k_1\left(\frac{V_D}{v_h}\right) + k_2\left(\frac{V_D}{v_h}\right)^2 + k_3\left(\frac{V_D}{v_h}\right)^3 + k_4\left(\frac{V_D}{v_h}\right)^4 \tag{31}$$

with $k = 0.974$, $k_1 = -1.125$, $k_2 = -1.372$, $k_3 = -1.718$, and $k_4 = -0.655$.

**Figure 8** shows the graphical results from this analysis, made in the Maple soft program.

In the normal working state of the rotor, if the climb velocity increases, the induced velocity decreases and also, in the windmill brake state if the descent velocity increases the induced velocity decreases and asymptotes to zero at high descent rates. In the vortex ring region, the induced velocity is approximated, because momentum theory cannot be applied. The flow in this region is unsteady and turbulent having upward and downward velocities. During normal powered flight, the rotor generates an induced airflow going downward and there is a recirculation of air at the blade tips, having the form of vortices, which exist because higher pressure air from below the rotor blade escapes into the lower pressure area above the blade. The rate of descent that is required to get into the vortex ring state varies with the speed of the induced airflow. Although vortices are always present around the edge of the rotor disk, under certain airflow conditions, they will intensify and, coupled with a stall spreading outward from the blade root, result in a sudden loss of rotor thrust. Vortex ring can only occur when the following conditions are present: power on, giving an induced flow down through rotor disk; a rate of descent, producing an external airflow directly opposing the induced flow; low forward speed.

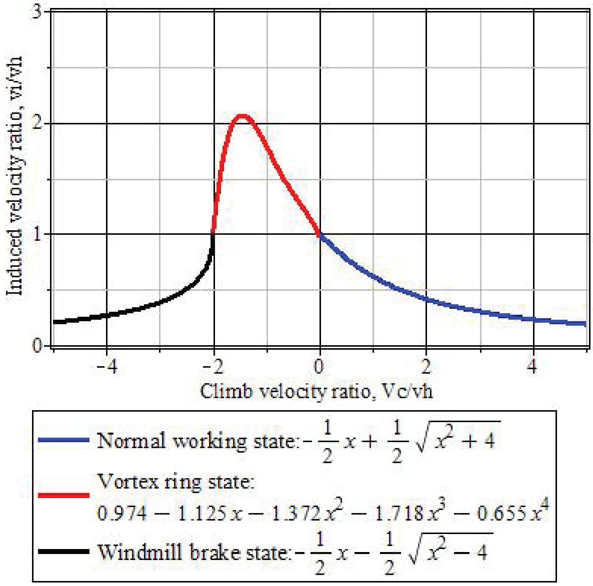


**Figure 8.** Induced velocity variation.

### 2.4. Power required in axial climbing and descending flight

In a climb or descent, the power ratio is

$$\frac{P}{P_h}=\frac{V_{C,D}+v_i}{v_h}=\frac{V_{C,D}}{v_h}+\frac{v_i}{v_h} \tag{32}$$

Using Eqs. (20) and (30), and substituting in the above equation, it follows that

- For a climb: $\frac{P}{P_h}=\frac{1}{2}\frac{V_C}{v_h}+\sqrt{\frac{1}{4}\left(\frac{V_C}{v_h}\right)^2+1}$, which is valid for $\frac{V_C}{v_h}\geq 0$;
- For a descent: $\frac{P}{P_h}=\frac{1}{2}\frac{V_D}{v_h}-\sqrt{\frac{1}{4}\left(\frac{V_D}{v_h}\right)^2-1}$, which is valid for $\frac{V_C}{v_h}\leq -2$;

For the vortex ring state, we can use the approximation (31) for the induced velocity ration, therefore in this case, the power ratio is

$$\frac{P}{P_h}=\frac{V_D}{v_h}+\frac{v_i}{v_h}=\frac{V_D}{v_h}+k+k_1\left(\frac{V_D}{v_h}\right)+k_2\left(\frac{V_D}{v_h}\right)^2+k_3\left(\frac{V_D}{v_h}\right)^3+k_4\left(\frac{V_D}{v_h}\right)^4 \tag{33}$$

Using the same Maple soft program like for induced velocity, we obtain the following picture for the power ratio, $P/P_h$.

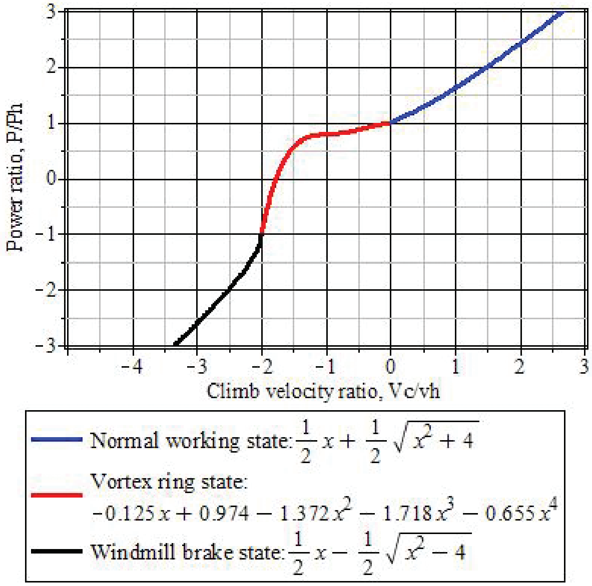


**Figure 9.** Power required as a function of climb and descent velocity.

According to the power to power in hover ratio values, shown in **Figure 9**, the power required to climb is always greater than the power required to hover, namely this ratio is greater than unity. In descent flight, the rotor extracts power from the air and uses less power than to hover.

### 2.5. Induced velocity in forward flight

In forward flight, the rotor must be tilted (**Figure 10**) in order to have a propulsive force to propel the helicopter forward, with a velocity $V_\infty$. This velocity has two components: one component normal to the rotor disk plane, $V_\infty \sin\alpha$, and another component, parallel to the rotor disk plane, $V_\infty \cos\alpha$.

The rotor thrust, $T$, is given by $T = 2\rho A v_i \sqrt{(V_\infty \cos\alpha)^2 + (V_\infty \sin\alpha + v_i)^2}$ and the induced velocity in forward flight can be written as

$$v_i = \frac{\frac{T}{2\rho A}}{\sqrt{(V_\infty \cos\alpha)^2 + (V_\infty \sin\alpha + v_i)^2}} = \frac{v_h^2}{\sqrt{(V_\infty \cos\alpha)^2 + (V_\infty \sin\alpha + v_i)^2}} \quad (34)$$

In order to get an analytical solution for the induced velocity, it is necessary to define two coefficients: *the advance ratio*, $\mu$, and *the inflow ratio*, $\lambda$, as it follows

$$\mu = \frac{V_\infty \cos\alpha}{R\Omega} \tag{35}$$

$$\lambda = \frac{V_\infty \sin\alpha + v_i}{R\Omega} = \frac{V_\infty \sin\alpha}{R\Omega} + \frac{v_i}{R\Omega} = \mu \tan\alpha + \lambda_i \tag{36}$$

Dividing Eq. (34) to $R\Omega$, we get

$$\frac{v_i}{R\Omega} = \lambda_i = \frac{\frac{v_h^2}{(R\Omega)^2}}{\sqrt{\left(\frac{V_\infty \cos\alpha}{R\Omega}\right)^2 + \left(\frac{V_\infty \sin\alpha + v_i}{R\Omega}\right)^2}} = \frac{\lambda_h^2}{\sqrt{\mu^2 + \lambda^2}} \tag{37}$$

This expression leads to the following equation for the inflow ratio, $\lambda$,

$$\lambda = \mu \tan\alpha + \frac{\lambda_h^2}{\sqrt{\mu^2 + \lambda^2}}, \text{ or } \frac{\lambda}{\lambda_h} = \frac{\mu}{\lambda_h} \tan\alpha + \frac{1}{\sqrt{\left(\frac{\mu}{\lambda_h}\right)^2 + \left(\frac{\lambda}{\lambda_h}\right)^2}} \tag{38}$$

The above equation can be very easy to be solved in Maple soft. In **Figure 11**, three curves are shown, in coordinates $\frac{\mu}{\lambda_h}$ and $\frac{\lambda}{\lambda_h}$, representing three values of angle $\alpha$, namely $\alpha = 0$ deg, $\alpha = 4$ deg, and $\alpha = 6$ deg. The command plot used in Maple was "*implicitplot*" for the equation $y = x \cdot \tan\alpha + \frac{1}{\sqrt{x^2+y^2}}$.

The inflow ratio, $\lambda/\lambda_h$ increases with the increase of the rotor disk angles of attack.

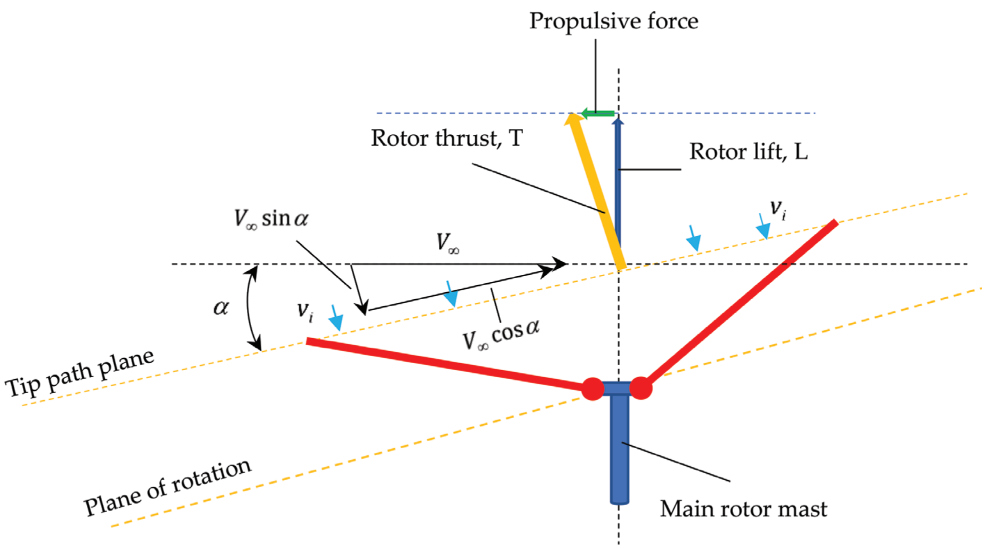


**Figure 10.** Rotor in forward flight.

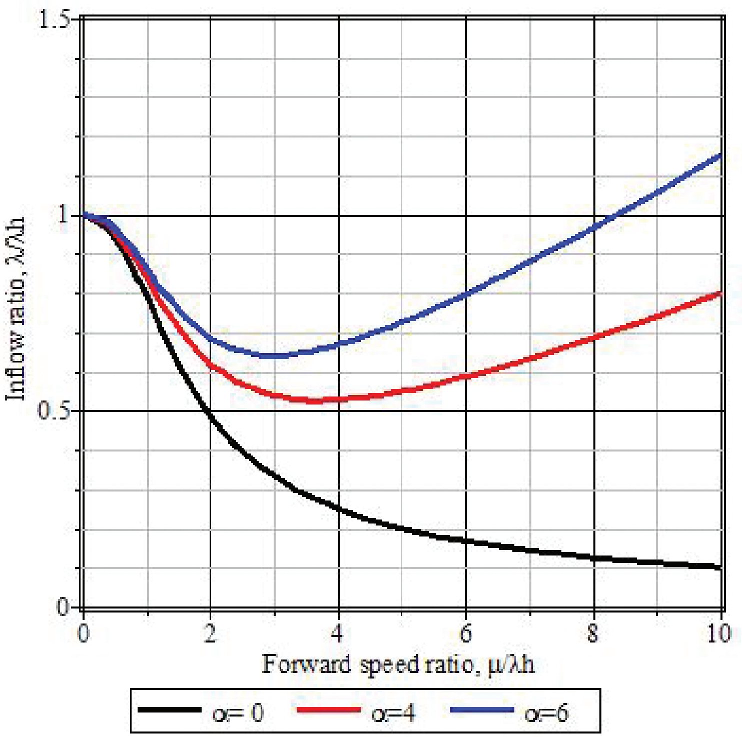


**Figure 11.** Inflow ratio $\lambda/\lambda_h$ as a function of forward speed ratio.

## 3. Helicopter systems

### 3.1. Main rotor systems

The primary way to distinguish between different main rotor systems is represented by the movement of the blade relative to the main rotor hub. The main categories are fully articulated, semi rigid, and rigid. In hovering flight, the blades flap up and lag back with respect to the hub and reach equilibrium position under the action of aerodynamic and centrifugal forces. In forward flight, the asymmetry of the dynamic pressure over the disk produces aerodynamic forces that are the functions of the blade azimuth position. The hinges allow each blade to independently flap and lead or lag with respect to the hub plane. The lead-lag hinge allows in-plane motion of the blade due to the Coriolis and radius of gyration changing in flapping movement. Transition from hover to forward flight introduces additional aerodynamic forces and effects that are not found when the helicopter is in stationary hover. Due to the difference in relative airspeed between the advancing and retreating blades, the lift is constantly changing through each revolution of the rotor.

**Figure 12** shows the flapping, lead-lag, and feathering motion of a rotor blade.

In a fully articulated rotor, each main rotor blade is free to move up and down (flapping), to move forth and back (dragging), and to twist about the spanwise axis (feathering). Semi rigid rotor has, normally, two blades attached rigidly to the main rotor hub and is free to tilt and rock independently of the main rotor mast, one blade flaps up and other flaps down.

The rigid rotor system cannot flap or drag, but it can be feathered. The natural frequency of the rigid rotor is high, so the stability is difficult to be achieved.

### 3.2. Anti-torque system

The single rotor helicopters require a separate rotor to overcome the effect of torque reaction, namely the tendency for the helicopter to turn in the opposite direction to that of the main rotor. The anti-torque pedals are operated by the pilot's feet and vary the force produced by the tail rotor to oppose torque reaction.

### 3.3. Swash plate assembly

It has the purpose to transmit cyclic and collective control movements to the main rotor blades and consists of a stationary plate and a rotating plate. The stationary plate is attached to the

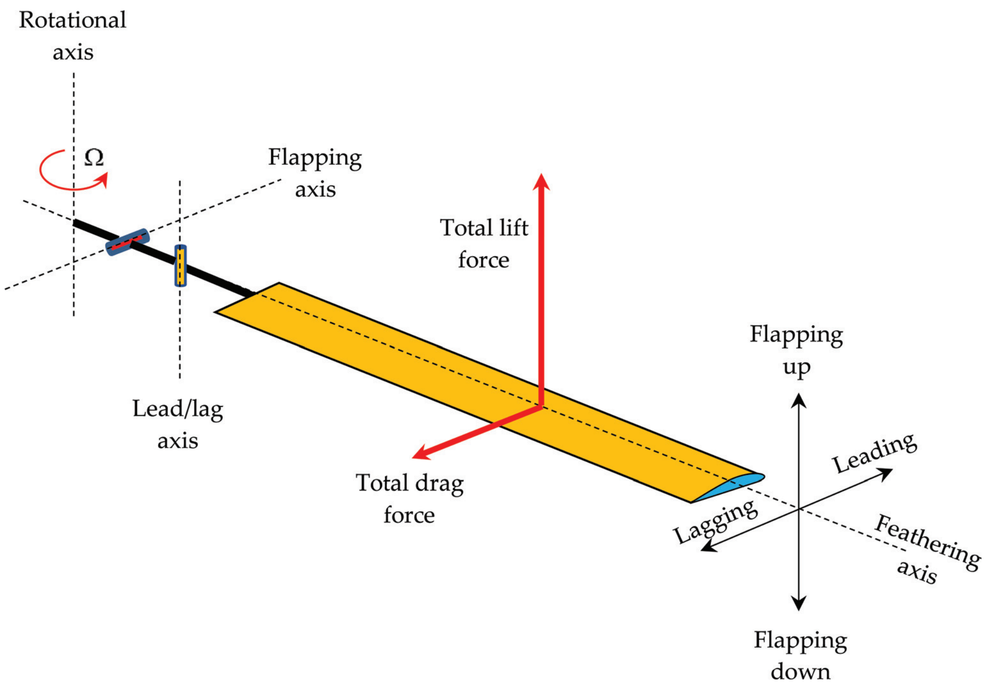


**Figure 12.** Blade movement axis.

main rotor mast and the rotating plate is attached to the stationary plate by a bearing surface and rotates at the same speed as the main rotor blades.

### 3.4. Trim

The neutral position of the cyclic stick changes as the helicopter moves off from to hover in forward flight. Trim control can adjust the mechanical feel in flight by changing the neutral position of the stick.

### 3.5. Collective and cyclic pitch control

Collective pitch lever controls the lift produced by the rotor, while the cyclic pitch controls the pitch angle of the rotor blades in their cyclic rotation. This tilts the main rotor tip-path plane to allow forward, backward, or lateral movement of the helicopter.

## 4. Power

### 4.1. Power required

The power required for flight is the second work that must be transmitted to the shaft of the rotor.

In general, for a helicopter in forward flight, the total power required at the rotor, $P$, can be expressed by the equation

$$P = P_i + P_o + P_P + P_y \tag{39}$$

where $P_i$ is the induced power, $P_0$ is the profile power required to overcome viscous losses at the rotor, $P_P$ is the parasitic power required to overcome the drag of the helicopter, and $P_y$ is the climb (or descend) power required to increase (decrease) the gravitational potential of the helicopter [1].

Inductive power is consumed to produce lift equal to the weight of the helicopter. From the simple 1-D momentum theory the induced power of the rotor, $P_i$, can be approximated as

$$P_i = k \cdot T \cdot v_i \tag{40}$$

where $k$ is the familiar empirical correction to account for a multitude of aerodynamic phenomena, mainly those resulting from tip losses and nonuniform inflow, and $v_i$ is induced velocity [1].

The profile power required to overcome the profile drag of the blades of the blades of the rotor is

$$P_0 = Q \cdot \Omega \tag{41}$$

where $Q$ is the rotor torque, and $\Omega$ is the rotational frequency of the rotor.

The parasite power, $P_P$, is a power loss as a result of viscous shear effects and flow separation (pressure drag) on the fuselage, rotor hub, and so on. Because helicopter fuselages are much less aerodynamic than their fixed-wing counterparts (for the same weights), this source of drag can be very significant [1]. The parasite power can be written as

$$P_P = D \cdot V \tag{42}$$

The climb (or descend) power can be written as

$$P_y = T\left(v_i \pm V_y\right) \tag{43}$$

where $V_y$ is the climb (or descend) velocity. In hover regime $V_y = 0$.

In addition, when calculating the power required of the helicopter, the required power of the tail rotor must also be calculated. The power required by the tail rotor typically varies between 3 and 5% of the main rotor power in normal flight, and up to 20% of the main rotor power at the extremes of the flight envelope [1]. It is calculated in a similar way to the main rotor power, with the thrust required being set equal to the value necessary to balance the main rotor torque reaction on the fuselage. The use of vertical tail surfaces to produce a side force in forward flight can help to reduce the power fraction required for the tail rotor, albeit at the expense of some increase in parasitic and induced drag.

**Figure 13** shows the net power required for a given helicopter in straight-and-level flight.

### 4.2. Power available

The power needed to rotate the main rotor transmits to the main rotor from the engine through the transmission (**Figure 13**). But the main rotor cannot get all the power, which is developed from the engine, as part of it is spent for other purposes and does not go to the main rotor.

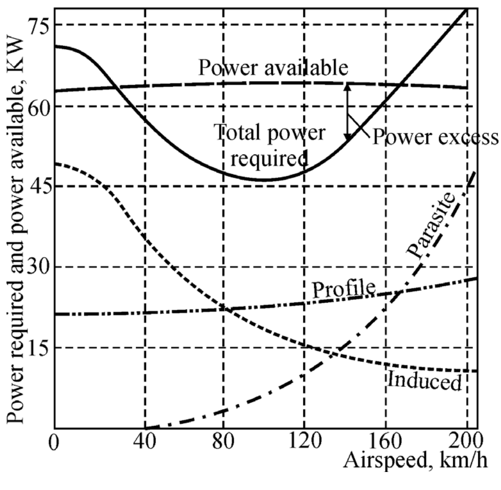


**Figure 13.** Power required and power available in straight-andlevel flight.

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For rotating of the tail rotor about 8% is lost from the consumed power of the engine, for fan rotation about 5%, for friction about 7% in transmission, for auxiliary drive units about 1%, and for blowing parts of the helicopter about 2%.

This part of the power of the motor that is transmitted to the main rotor is called available power. It is defined as the difference between effective power and total loss.

Excess power—this is the difference between the available and the power required. The greater the excess power is, the greater the speed range is and the better the helicopter's maneuvering characteristics are (**Figure 13**).

## 5. Ground effect

When the helicopter flies near the earth's surface, the efficiency of the rotor system increases because of the interference of the airflow with the ground [2–4]. The rotor downwash is unable to escape as readily as it can when flying higher and creates a ground effect. When the rotor downwash reaches the surface, the induced flow downwash stops its vertical velocity, which reduces the induced flow at the rotor disk (**Figure 14**).

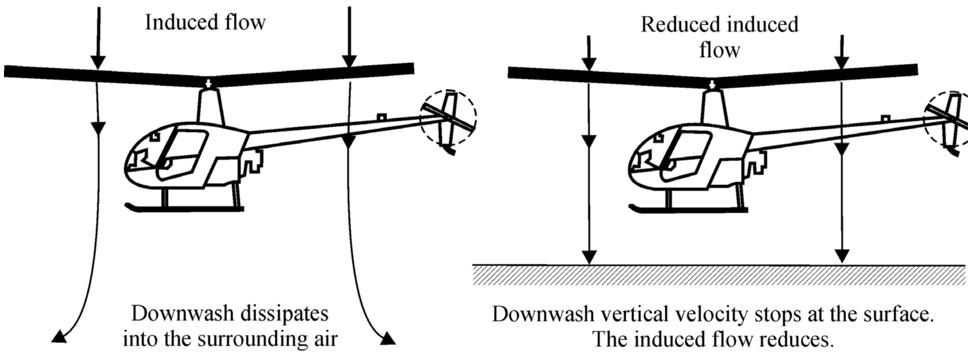


**Figure 14.** Influence of ground effect on the induced flow.

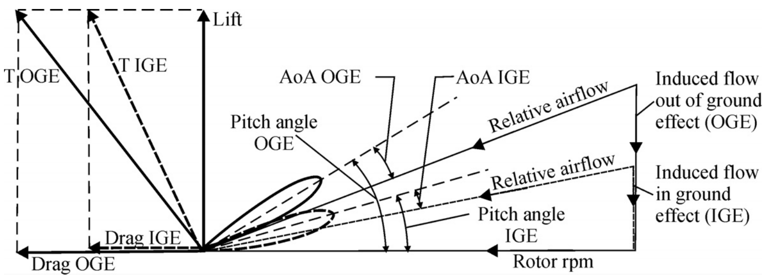


**Figure 15.** Influence of ground effect on the rotor drag.

**Figure 15** shows the effects of this on the power required to hover. If the hover height in ground effect must be maintained, the aircraft can only be kept at this height by reducing the angle of attack (AoA) so that the total reaction produces a rotor lift exactly equal and opposite to weight. It shows that the angle of attack is slightly less, the amount of total rotor thrust is the same as the gross weight, the blade angle is smaller, the power required to overcome the reduced rotor drag (or torque) is less and the collective control lever is lower than when hovering out of ground effect. Therefore, there is better lift/drag ratio.

These conclusions are also true to flight in ground effect other than the hover, but the effect is smaller.

## 6. Autorotation

Autorotation is an emergency mode. It can arise if the engine stops in flight (usually without the pilot's desire), when the rotor is not driven by the engine and begins to rotate by aerodynamic forces resulting from rate of oncoming airflow through the rotor [1, 3].

### 6.1. Vertical autorotation

In the case of vertical autorotative descent (without forward speed) without wind, the forces that cause a rotation of the blades are similar for all blades, regardless of their azimuth position [2].

During vertical autorotation, the rotor disk is divided into three regions (as illustrated in **Figure 16a**): driven region, driving region, and stall region. **Figure 17** shows the blade sections that illustrate force vectors. Force vectors are different in each region, as the relative air velocity is lower near the root of the blade and increases continually toward its tip. The combination of the inflow up through the rotor with the relative air velocity creates different aerodynamic forces in each section along the blade [2].

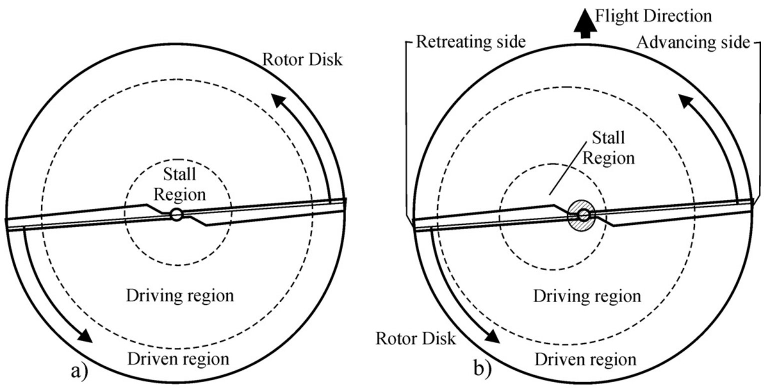


**Figure 16.** Autorotation regions in (a) vertical descend and (b) forward autorotation descend.

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In the driven region, illustrated in **Figure 17**, the section aerodynamic force T acts behind the axis of rotation. This force has two projections: the drag force D and lift force L. In this region, the lift is offset by drag, and the result is a deceleration of the blade rotation. There are two sections of equilibrium on the blade—the first is between the driven area and the driving region, and the second is between the driving region and the stall region. At the equilibrium sections, the aerodynamic force T coincides with the axis of rotation. There are lift and drag forces, but neither acceleration nor deceleration is induced [2].

In the driving region, the blade produces the forces needed to rotate the blades during the autorotation. The aerodynamic force in the driving region is inclined slightly forward with respect to the axis of rotation. This inclination provides thrust that leads to an acceleration of the blade rotation. By controlling the length of the driving region, the pilot can adjust the autorotative rpm [2].

In the stall region, the rotor blade operates above its stall angle (maximum angle of attack), causing drag, which tends to slow rotation of the blade.

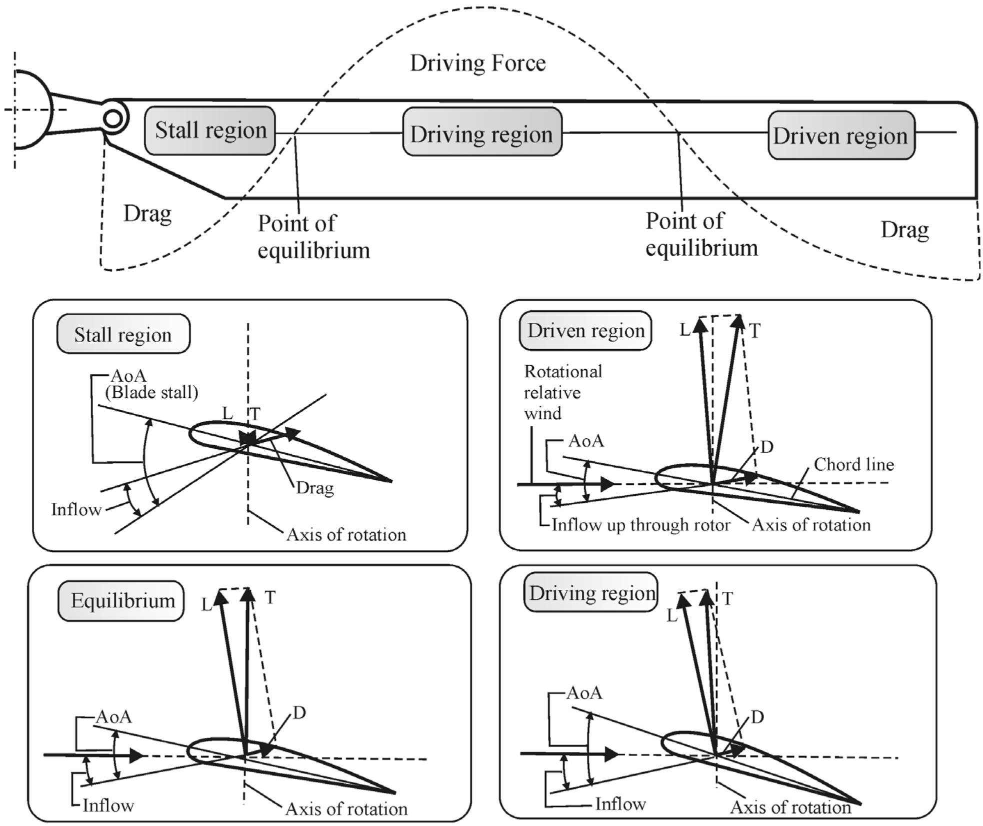


**Figure 17.** Force vectors in vertical autorotation.

### 6.2. Autorotation in forward descend

Autorotative force in forward flight is produced in exactly the same scheme as when the helicopter is descending vertically in still air. However, because of the forward flight velocity there is a loss of axial symmetry in the induced velocity and angles of attack over the rotor disk. This tends to move the distribution of parts of the rotor disk that consume power and absorb power, as shown in **Figure 16b**. A small section near the root experiences a reversed flow; therefore, the size of the driven region on the retreating side is reduced [1].

## 7. Helicopter stability and control

### 7.1. Helicopter stability

Helicopter stability means its ability in the conditions of external disturbances to keep the specified flight regime without pilot management [3, 5].

Let us consider the longitudinal motion of a helicopter on the hovering regime (**Figure 18**). The weight of the helicopter $W$, attached to the helicopter's CG, is balanced by the thrust force of the main rotor $T$, applied at a point removed on the vertical axis by the distance $z$ (see **Figure 18a**).

Recall that a helicopter, like any aircraft, is considered statically stable, if it after a deviation from the steady flight regime tends to return to its original position. Suppose, for example, that as a result of the action of a wind gust $U$ the thrust $T$ is deflected backward (see **Figure 18b**). The tilt of the thrust will result in the appearance of a horizontal component $D$ acting backwards and a longitudinal pitching moment $M = Dz$. Under the action of the horizontal component, the helicopter will start to move back with a speed $V_x$, and under the action of the moment $M$ it will start to rotate relative to the roll axis, increasing the pitch angle with the angular velocity $q$ (see **Figure 18c**).

Both effects: both the translational velocity and the rotation of the fuselage, and hence the axis of the rotor, will cause the resultant forces $T$ on the rotor to tilt to the same side, opposite to the original inclination. This will cause the appearance of a horizontal component and a longitudinal moment, already oppositely directed, due to which the helicopter will tend to return to the initial pitch angle and to zero forward speed. This means that the helicopter is statically stable in pitch angle and hover speed. Its static stability is due to the properties mentioned above: speed stability and damping.

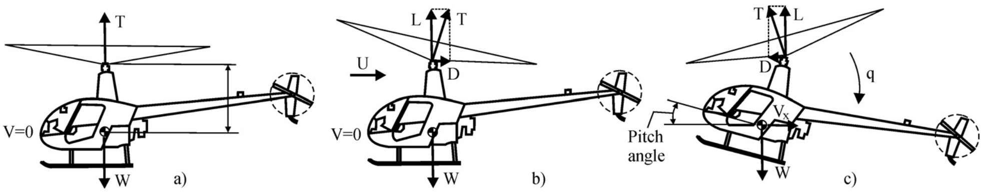


**Figure 18.** Longitudinal motion of the helicopter in hover.

Consider, however, the further movement of the helicopter. The inclination of the resultant in the direction of parrying disturbance is too great because of the presence of velocity stability. It leads to the fact that the helicopter in its movement to the initial position skips the equilibrium position and deviates in the opposite direction, but already by a large magnitude. The motion of the helicopter takes the character of oscillation with increasing amplitude. The aircraft, which in the free disturbed motion ultimately leave the initial equilibrium state, is called dynamically unstable. Thus, a helicopter on a hovering regime is dynamically unstable.

The given case relates to the helicopter's movement on the pitch angle on the hover. The roll motion on the hover has a similar character. The difference here is manifested only in the period and the degree of growth of oscillation, which depend on the moments of inertia of the helicopter, different in pitch and roll.

The helicopter is neutral in the yaw angle and the altitude on the hover. This means that the helicopter does not tend to keep a given course angle or a given flight altitude. At the corresponding disturbances these parameters will change. But their change will continue only as long as the perturbation is working. At the end of the disturbance, the course angle and altitude will not change.

It can be said that the helicopter is stable with respect to the yaw rate and the vertical speed. This stability is explained by the fact that the main rotor at an increase of the airspeed in a direction opposite to the thrust reduces its thrust, and conversely, when this speed decreases—increases the thrust, thus creating a damping force in the direction of the axis of rotation. Therefore, the tail rotor creates a large damping yaw moment on the helicopter, and the main rotor—a damping force for vertical helicopter movements.

In forward flight, the efficiency of helicopter control and the derivatives of the damping moments and moments of stability with respect to the main rotor speed vary insignificantly. However, the moment derivative with respect to the angle of attack, which for the main rotor corresponds to the instability, begins to play an important role. This instability can be compensated if the fuselage of the helicopter has a stabilizer, which improves the desired degree of stability in the angle of attack. But it is difficult to provide satisfactory longitudinal stability even with well-designed stabilizer. That's why the modern helicopters are equipped with electronic stabilization.

In the forward flight, the roll movement is strongly connected with the yaw movement, just as it does on the airplane. These two movement types are therefore referred to as one, "lateral" movement of the helicopter. The own lateral motion of a single-rotor helicopter during a forward flight, as a rule, is periodically stable. In the low-speed modes, while the relationship between the roll and yaw movements is still small, and the roll motion, like the hovering, is unstable, the lateral motion of a single-rotor helicopter is unstable.

Static stability of helicopters with two main rotors differs slightly from the stability of the helicopter with one main rotor. The tandem main rotor helicopter has a significantly greater longitudinal static stability, and the coaxial main rotor helicopter has a greater lateral stability. This is explained by the change of main rotors thrust at a disruption of the equilibrium.

So, the helicopter, essentially, cannot maintain a steady flight regime. The pilot, piloting the helicopter, continuously has to act on the helicopter's controls and create control moments, under which the helicopter to maintain the specified flight regime.

### 7.2. Helicopter control

Control characteristics refer to a helicopter's ability to respond to control inputs and so move from one flight condition to another [6]. There are four basic controls used during flight. They are the collective pitch control, the throttle, the cyclic pitch control, and the antitorque pedals (**Figure 19**).

### 7.3. Collective pitch control

The collective pitch control changes the pitch angle of all main rotor blades. The collective is controlled by the left hand (**Figure 19**). As the pitch of the blades is increased, lift is created

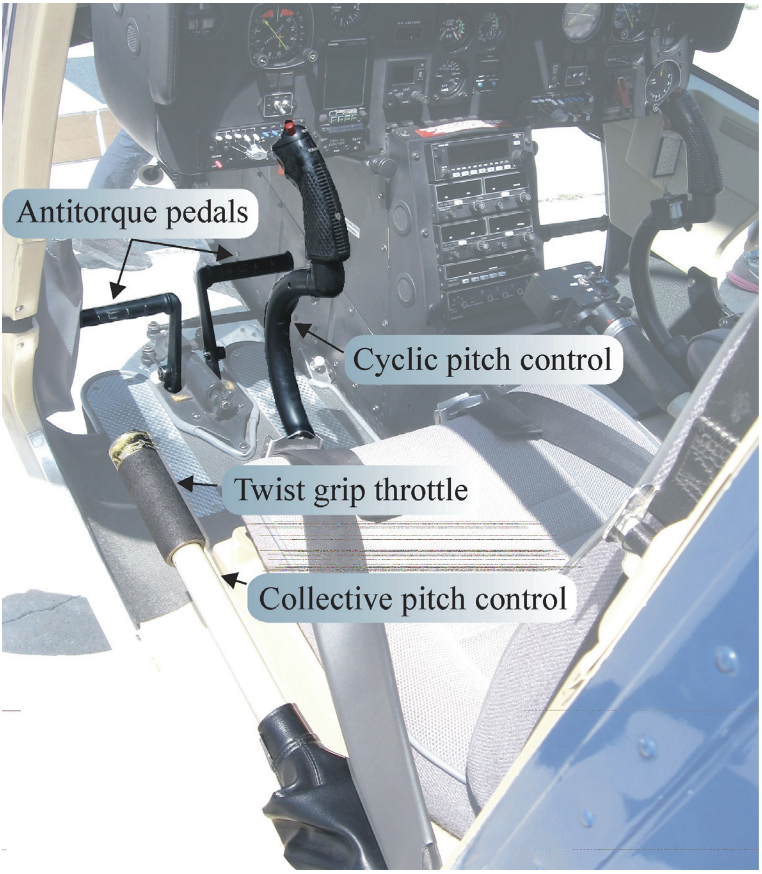


**Figure 19.** Basic helicopter controls.

causing the helicopter to rise from the ground, hover or climb, as long as sufficient power is available.

The variation of the pitch angle of the blades changes the angle of attack on each blade. The change in the angle of attack causes a change in the drag, which reflects the speed or rpm of the main rotor. When the pitch angle increases, the angle of attack increases too, therefore the drag increases, and the rotor rpm decreases. When the pitch angle decreases, the angle of attack and the drag decrease too, but the rotor rpm increases. To maintain a constant rotor rpm, which is specific to helicopters, a proportional alteration in power is required to compensate for the drag change. This is achieved with a throttle control or a correlator and/or governor, so that the engine power can be regulated automatically [2].

### 7.4. Throttle control

The purpose of the throttle is to regulate engine rpm if the system with a correlator or governor does not maintain the necessary rpm when the collective is raised or lowered, or if those devices are not installed, the throttle has to be moved manually with the twist grip to maintain desired rpm. Twisting the throttle outboard increases rpm; twisting it inboard decreases rpm [2].

The correlator is a device that connects the collective lever and the engine throttle. When the collective lever raises, the power automatically increases and when lowers, the power decreases. The correlator maintains rpm close to the desired value, but still requires an additional fine tuning of the throttle. The governor is a sensing device that recognizes the rotor and engine rpm and makes the necessary settings to keep rotor rpm constant. Under normal operation, once the rotor rpm is set, the governor keeps the rpm constant, and there is no need to make any throttle settings. The governor is typical device used in turbine helicopters and is also used in some helicopters with piston engines [2].

### 7.5. Cyclic pitch control

The rotor control is performed by the cyclic pitch control, which tilts the main rotor disk by changing the pitch angle of the rotor blades. The tilting rotor disk produces a cyclic variation of the blade pitch angle. When the main rotor disk is tilted, the horizontal component of thrust moves the helicopter in the tilt direction.

**Figure 20** shows the conventional main rotor collective and cyclic controls. The controls use a swash plate. The collective control applies the same pitch angle to all blades and is the main tool for direct lift or thrust rotor control. Cyclic is more complicated and can be fully appreciated only when the rotor is rotating. The cyclic operates through a swash plate (**Figure 20**), which has non-rotating and rotating plates, the latter attached to the blades with pitch link rods, and the former to the control actuators [7].

### 7.6. Antitorque pedals

Two anti-torque pedals are provided to counteract the torque effect of the main rotor. This is done by increasing or decreasing the thrust of the tail rotor (**Figures 19** and **21**). The torque varies with changes in main rotor power; therefore, the tail rotor thrust is necessary to change

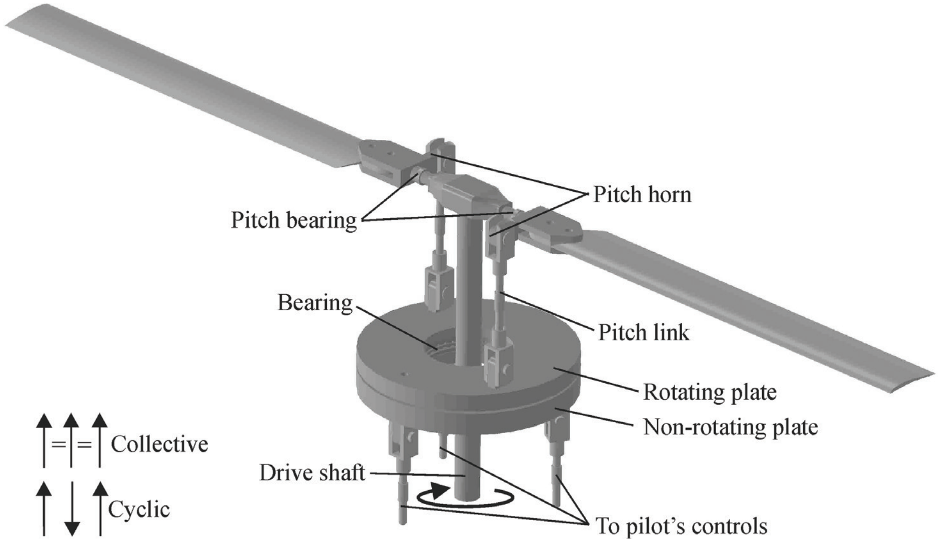


**Figure 20.** Rotor control through a swash plate.

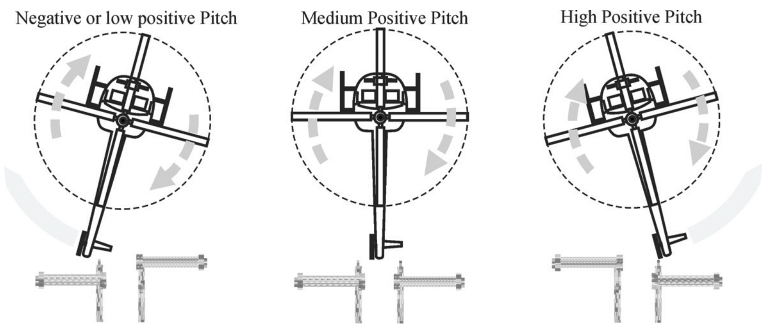


**Figure 21.** Tail rotor pitch angle and thrust in relation to pedal positions during cruising flight.

too. The pedals are connected to the pitch change device on the tail rotor gearbox and enable the pitch angle of the tail rotor blades to increase or decrease [2].

## 8. Flight performance

The pilot's ability to determine, in advance, the helicopter's flying characteristics is of utmost importance. It is very important to determine what maximum weight the helicopter can carry before take-off, if the helicopter can safely hover at a given altitude and temperature, what distance is needed to climb above the obstacles, and what is the maximum climb rate [2].

### 8.1. Factors affecting performance

There are many factors that influence a helicopter's performance in flight. The most important ones are: altitude, including pressure altitude and density altitude, helicopter gross weight, and the wind.

### 8.2. Altitude

One of the most important factors in helicopter performance is the air density, which decreases with a gain in altitude. The effect of altitude is shown in **Figure 22a**. Increasing density altitude increases the power required in hover and lower airspeeds. At higher airspeeds, the results of lower air density result in a lower power requirements because of the reduction of parasitic drag. A higher density altitude also affects the engine power available. The power available at a higher density altitude is less than that at a lower one. As a result there is a decrease in the excess power at any airspeed [1].

### 8.3. Weight

Increases in aircraft gross weight go hand in hand with requirements for higher angles of attack and more power. As shown in **Figure 22b**, by increasing the weight, the excess power becomes less, but it is particularly affected at lower airspeeds because of induced drag [1].

High gross weight also affects of the maximum height at which the helicopter can operate in ground effect for a given power available. Under these conditions, the heavier the helicopter is, the lower the maximum hover altitude is [3].

### 8.4. Wind

Wind direction and velocity also affect hovering, takeoff, and climb performance. Translational lift occurs any time when there is relative airflow over the rotor disk. This explains whether the relative airflow is caused by helicopter movement or by the wind. With the increase in the wind speed, the translational lift increases, therefore less power is required in hovering [2].

Besides the magnitude of wind velocity, its direction is essential. Headwind is the most desirable because it gives the greatest increase in performance. Strong crosswind and tailwind require the

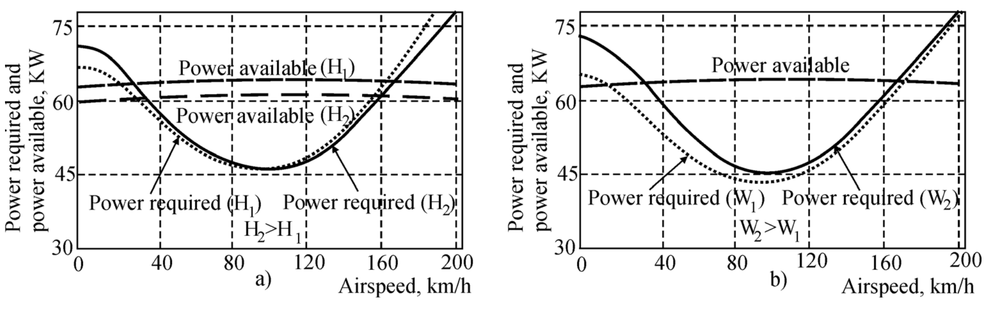


**Figure 22.** Power required and power available at (a) different altitudes, and (b) different weights.

more tail rotor thrust to maintain the directional control. The increased tail rotor thrust takes away a power from the engine, and therefore will have less power available to the main rotor, which produces the required lift. Some helicopters have a critical wind azimuth limits and the manufacturer presents maximum safe relative wind chart. If the helicopter operates above these limits, it can cause a loss of tail rotor control [2].

### 8.5. Performance charts

When developing performance charts, aircraft manufacturers make some assumptions about the operating helicopter conditions and the pilot's ability. It is supposed that the helicopter is in good operating condition and the engine is able to develop its rated power. It is assumed that the pilot performs normal operating procedures and he has average flying abilities [2].

With these assumptions, the manufacturer develops performance data for the helicopter taking into account the flight tests. But the helicopter is not tested under all conditions shown on the performance chart. Instead, an evaluation of the specific data is performed and the remaining data are obtained in mathematical way [2].

Generally, the charts present graphics related to hover power: in ground effect (IGE) hover ceiling vs. gross weight, and out of ground effect (OGE) hover ceiling vs. gross weight. The exact names of these charts may vary by different helicopter manuals. These are not the only charts, but these charts are perhaps the most important charts in each manual—they help to understand the amount of power which the helicopter have to have under specific operating conditions (altitude, gross weight, and temperature).

## 9. Conclusion

In this chapter, an analysis for defining the helicopter's performance was performed. It has been shown that the performance characteristics can be derived by using simple models as the momentum and blade elements theories. The impact of weight and altitude on the required power and the available power has been presented. The effect of near the ground operation on the helicopter's performance is discussed. Also, the case when the engine stops in flight and the main rotor performs autorotation is presented. Some elementary analysis of the stability characteristics has been done. The impact of different helicopter parts on the stability has been considered. Finally, it has been shown how the helicopter can be controlled.

## Author details

Constantin Rotaru[1]* and Michael Todorov[2]

*Address all correspondence to: rotaru.constantin@afahc.ro

1 "Henri Coanda" Air Force Academy, Brasov, Romania

2 Technical University of Sofia, Bulgaria

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## References

[1] Leishman G. Principles of Helicopter Aerodynamics. 1st ed. Cambridge: Cambridge University Press; 2000. p. 495

[2] Johnson W. Helicopter Theory. New York: Dover Publications; 1994. p. 1085

[3] Wagtendonk W. Principles of Helicopter Flight. 2nd ed. Newcastle: Aviation Supplies & Academics Inc.; 2015. p. 304

[4] Johnson W. Rotorcraft Aeromechanics. 1st ed. New York: Cambridge University Press; 2013. p. 927

[5] Prouty R. Helicopter Performance, Stability, and Control. 3rd ed. Florida: Kreiger Publishing Company; 1995. p. 731

[6] Seddon J, Newman S. Basic Helicopter Aerodynamics. 3rd ed. Chichester: John Wiley & Sons; 2011. p. 255

[7] Padfield G. Helicopter Flight Dynamics. 2nd ed. Oxford: Blackwell Publishing; 2007. p. 641