Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Autonomous Systems Lab
Prof. Roland Siegwart

Studies on Mechatronics

From Kamov's first design to Micro Aerial Vehicles - a survey on coaxial helicopters

Spring Term 2009

Supervised by:
Christian Bermes

Author:
Michael Inglin

Contents

Abstract

This paper contains an overview over different coaxial concepts with respect to steering and altitude control. A comparison of the coaxial rotor configuration to other rotor configurations is made. A closer look is taken at the differences between coaxial and conventional helicopters. The evolution of coaxial helicopters is illustrated in a timeline. In a conclusion, reasons are given for the rare usage of the coaxial concept in full scale helicopter flight. Furthermore, possible future developments are shown.

List of Figures

List of Tables

Symbols

Ω	angular velocity of the rotor
x	x axis
y	y axis
z	z axis

Acronyms and Abbreviations

ETH	Eidgenössische Technische Hochschule
MAV	Micro Aerial Vehicle
UAV	Unmanned Aerial Vehicle
TsAGI	The Central Aerohydrodynamic Institute
PCT	Patent Cooperation Treaty
FAI	Fédération Aéronautique Internationale

Chapter 1

Introduction

The dream of flying is as old as mankind. Birds serve as the first inspirations for flying objects built by humans. After a lot of throwbacks in the development, the Wright-Brothers Orville and Wilbur flew the first time successfully with an aeroplane in 1903. Another kind of flying is the helicopter flight. Although helicopters are well known today as reliable flight objects, the development produces a lot more trouble than the aeroplane development. A reason is maybe that in nature no examples similar to helicopter flight exist.

Centuries ago, the first coaxial helicopters used as toys and curiosities existed. An interesting approach was developed by Leonardo Da Vinci shown in Figure 1.1. His helical airscrew was a first step in the direction of helicopter flight.

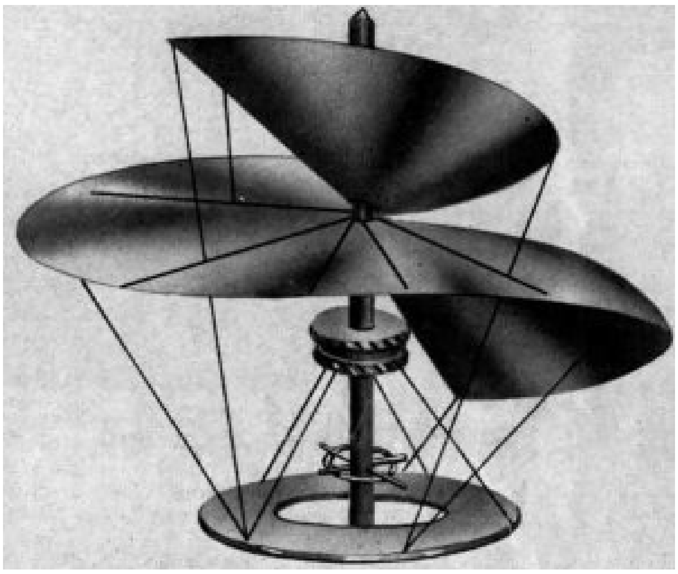
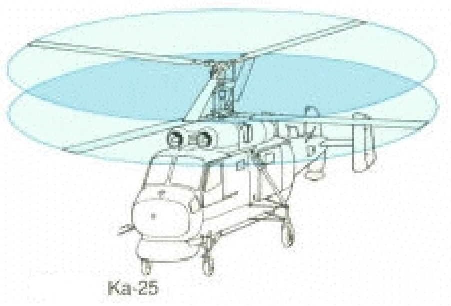


Figure 1.1: The helical airscrew by Leonardo Da Vinci [1].

In the evolution of helicopters, a lot of different variants and rotor configurations have been built. One of them is the coaxial rotor configuration, which is used up to the present. However, this configuration is rather non-standard in the full scale helicopter flight. This paper gives a closer look at the area of coaxial helicopters and shows their benefits and drawbacks compared to other rotor configurations.

1.1 The Definition of a Coaxial Helicopter

A coaxial helicopter consists of a pair of rotors turning in opposite directions. The rotors are mounted on a mast with the same axis of rotation. The two rotors are placed one above the other. This rotor configuration is mostly used by the Russian Kamov Company. Figure 1.2 shows a sketch (left) and an early variant of a coaxial helicopter (right).



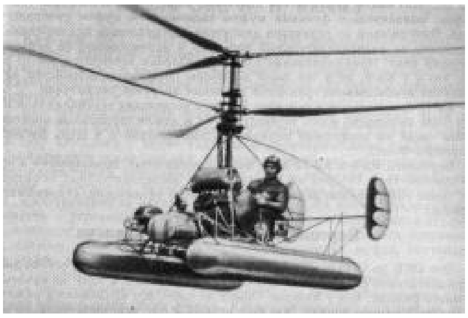


Figure 1.2: Sketch of a coaxial helicopter (left) [1] and a Kamov Ka-10 (right) [1].

1.2 The Coordinate System

In order to describe the position and the velocities of an aeroplane or a helicopter, a specific body linked coordinate system is introduced. Figure 1.3 shows this coordinate system. In general, all six degrees of freedom, which are the linear displacements and the rotations along the x, y and z axis, are possible for helicopters. The rotation around the z axis is called yaw. A helicopter is able to yaw nearly independent to the other degrees of freedom. Its altitude described by the z axis is independent from the other degrees of freedom. The rotation around the x axis is called roll. Around the y axis the rotation is described as pitch. The movement in x direction is coupled with the pitch angle of the helicopter. The same connection exists between the roll angle and the movement in y direction.

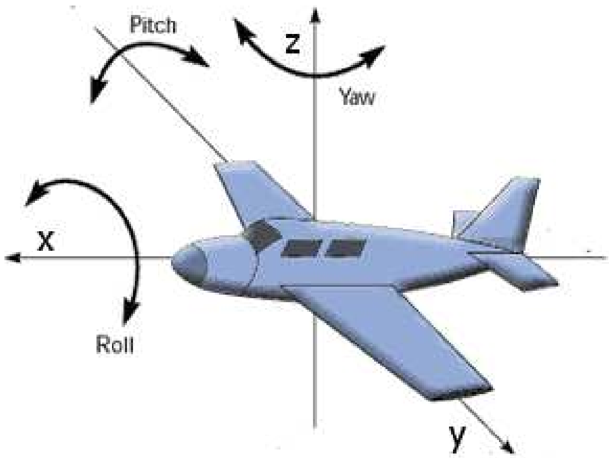


Figure 1.3: Coordinate system [2].

1.3 The Swashplate

Nearly all present full scale helicopters use a swashplate to control pitch, roll and altitude. The swashplate controls the angle of attack and as a result of this the produced lift force for the rotor blades. The swashplate is movable upwards and downwards, shown in Figure 1.4, along the rotor axis. These movements change the angle of attack, also called blade pitch for all rotor blades. This yields to a lift force dependent on the collective blade pitch adjusted from the swashplate.

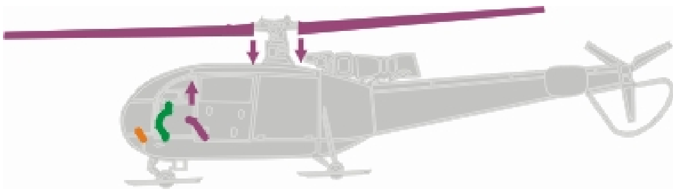


Figure 1.4: The effect of collective pitch [3].

In order to move the helicopter in the x-y plane, cyclic pitch is needed. This second possibility to control a helicopter is done by giving different pitch to the rotor blades during one rotation. In this configuration, the swashplate is tilted with respect to the rotor axis. This yields to a sinusoidal pitch angle for the rotor blades during one rotation. In order to move forward, the rotor disc has to be tilted in the position shown in Figure 1.5 (left). Due to the inertia and the aerodynamic forces, the maximum pitch angle induced from the cyclic pitch has to be adjusted some degrees before the desired highest position of the rotor disc. This forerun angle is dependent on the kind of the rotor and varies usually between 70 and 80 degrees. In order to move forward, the blades have the highest angle of attack on the right side of the helicopter when the rotor rotates clockwise. For the helicopter pilot these circumstances have not to be taken into account in order to control the flight position. By moving the stick forwards, the helicopter also moves forward. The control for roll and sidewards movements work in the same manner, shown in Figure 1.5.

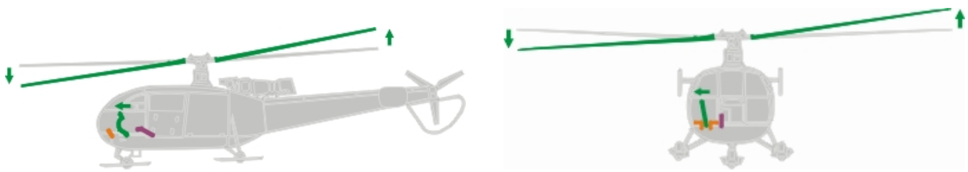


Figure 1.5: The effect of cyclic pitch dependent on the stick position [3].

1.4 Approach

As a first, appropriate literature is collected. With the aid of these resources, different aspects of coaxial helicopters are considered. In Chapter 2, diverse coaxial concepts with respect to steering and altitude control are described. The benefits and drawbacks of the different constructions are listed. In Chapter 3, other rotor concepts are described. These concepts are compared to the coaxial concept. The main comparison is done between the conventional and the coaxial configuration. In Chapter 4, the evolution of coaxial helicopters is described. Important improvements and innovations for the development of helicopters are mentioned. A survey is given by a timeline of the coaxial helicopter evolution. In Chapter 5, the conclusion and an outlook are given. The conclusion shows possible reasons for the rare usage of coaxial helicopters in full scale helicopter flight compared to the conventional configuration and its usage in Micro Aerial flight applications. The outlook includes future developments in helicopter flight with respect to coaxial helicopters.

Chapter 2

Coaxial Concepts

This chapter describes different coaxial concepts with respect to steering and altitude control. The four direct influenceable degrees of freedom, which are the translations in x, y and z axis and the rotation around the z axis, called yawing, are specified with assets and drawbacks. Furthermore, commonly used combinations of the steering variants are described and compared among each other.

2.1 Altitude Control

From a physical point of view there are two ways to change the altitude on a flying object. The influence on the acceleration in the z direction is shown in Equation 2.1. The two manipulable values are the mass m (change the $F_{\text{gravitation}}$) and the force F_{lift}. The method of reducing the total mass of a flying object by throwing away some ballast is used to control the altitude for gas balloons and seldom for hot-air balloons. This is not the preferred control principle for helicopters since it is not desired to transport extra ballast. The theoretically changeable variables in the force F_{lift} are the airspeed v, the blade surface A and the lift coefficient C_{L}. The parameter ρ in the Equation 2.2 is the fluid density, which is not influenceable.

$$m\ddot{z} = F_{\text{lift}} - F_{\text{gravitation}}, \tag{2.1}$$

$$F_{\text{lift}} = \frac{1}{2}\rho v^2 A C_{\text{L}}. \tag{2.2}$$

2.1.1 Changing the Airspeed

The airspeed has a quadratic influence on the produced lift force F_{lift}. Assuming the air has no relative movement to the earth, the airspeed on fixed-wing aircrafts is equal to the forward speed in the x direction. For helicopters, the airspeed on the rotor blades is not directly connected to the forward speed. By changing the angular velocity Ω of the two rotor shafts of the coaxial helicopter, the airspeed of the rotor blades can be changed. By increasing the actuator power, the moment M_{actuator} on the two rotor shafts increases, too. The drag moment M_{drag} consists of the induced drag[1] and the form drag[2]. As you can see in Figure 2.1, the induced drag moment M_{drag} has a strong dependency on the airspeed.

$$J_{\text{rotor}}\dot{\Omega} = M_{\text{actuator}} - M_{\text{drag}}. \tag{2.3}$$

[1] A drag force that occurs whenever a moving object redirects the airflow coming at it.
[2] A drag force caused by moving a solid object through a fluid.

It is desired that a steering input creates a reaction in flight level in a relatively short time. In order to fulfil this task, the inertia J_{rotor} of the rotor should be small and a big moment M_{actuator} should be provided by the actuator. Since the inertia of the rotor is difficult to reduce without changing other lift creating elements, a strong actuator with enough additional power to accelerate the rotor in a short time has to be installed. But a stronger actuator is normally heavier which requires a higher lift force F_{lift} to hold the flight level. These reasons make this way of altitude control for full scale helicopters not useful. The main problem is that the response time of altitude control inputs is too big. For small scale helicopters like MAVs or UAVs, altitude control with rotor angular velocity Ω variation is a possible way to go. Since the inertia decreases, it becomes small eonugh to realise acceptable altitude responses on the control inputs without having oversized actuators.

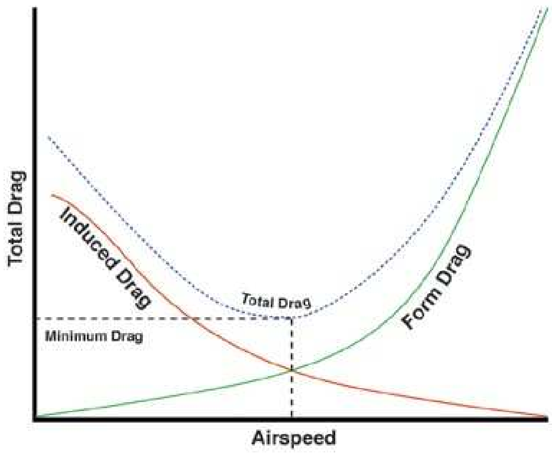


Figure 2.1: Example of a drag/airspeed diagram [4].

2.1.2 Changing the Blade Surface

The lift force F_{lift} is linearly dependent on the total blade surface A. Increasing the lift force by increasing the wing surface is a widely used mechanism for conventional aircrafts. These mechanisms are called flaps. The fowler flap[3] is a flap type which gives additional lift force by increasing the wing surface. Flaps are used for start and landing, in general during low speed flight. Since the blade speed of helicopters is not linked to the forward speed, additional lift force for start and landing is not necessary. Increasing the total blade surface A in helicopters during flight is a possible but not used mechanism to change the altitude. This kind of producing additional lift force is too complex for helicopters because extra actuators would be required in the rotor blades. The complexity and the weight of the rotor blades would grow in a disproportionate way comparing to the lift force benefit. In order to have sufficient lift force for the helicopter, a suitable number of blades with an accurate chord length is chosen in the helicopter design process. The increasing of the total rotor diameter influences the lift force in two ways. As a first, the total blade surface is increasing. As a second, the average velocity of the rotor blades increases, too.

[3]Creating a larger wing surface by sliding backwards before hinging downwards.

2.1.3 Changing the Lift Coefficient

The lift coefficient C_L influences the lift force F_lift in a proportional manner. The lift coefficient C_L is a dimensionless coefficient that relates the produced lift force F_lift to the other parameters of the Equation 2.2. The lift coefficient is dependent on the angle of attack. This connection is complex and can be determined either by experiments or complex analysis. Fortunately, the dependency between the lift coefficient and the angle of attack is nearly linear for small angles of attack. Figure 2.2 shows this dependency. At higher angles of attack, stall occurs and the lift coefficient decreases rapidly. The collective pitch provides the possibility to change the angle of attack in a short time. As a consequence, the helicopter reacts fast on steering inputs. Since it is not intended to begin yawing while changing the altitude, the collective pitch has to be changed on both rotor discs of a coaxial helicopter to balance the rotor torque.

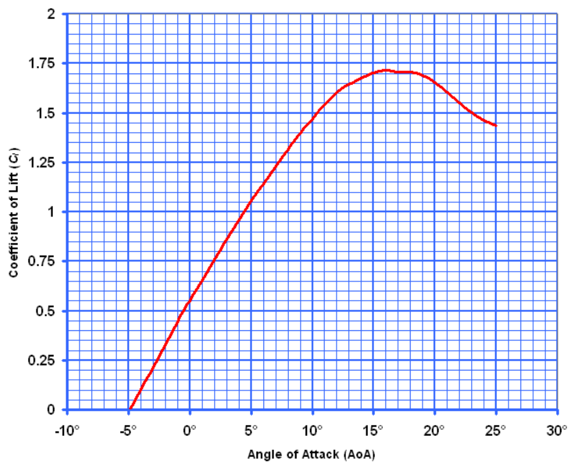


Figure 2.2: Example of an angle of attack/lift coefficient diagram [5].

2.2 Yaw Control

One of the big benefits of coaxial helicopters is the capability to control yaw without the necessity of additional actuators. Since the two rotors are counterrotating, the induced drags of the two rotors affect also in opposite direction. In order to control yaw, these two moments are either balanced or unbalanced. The most used method is the increasing of the collective pitch of one rotor and the simultaneous decreasing of the collective pitch of the other rotor. Since the induced moment raises by increasing the collective pitch, the helicopter begins to turn. In order to hold the flight level, the additional lift force generated by the higher collective pitch of one rotor is compensated by reducing the collective pitch of the other rotor. This is the standard yaw control principle, which is used by nearly all full scale coaxial helicopters including the ones from the Kamov Company. The drawback of this kind of yaw control is that the rotor head has a relatively complex design. This is due to the possibility of different coaxial pitch for the two rotors. A benefit is, that the helicopter needs only one actuator which supports both rotors with a constant rotor angular velocity Ω.

An approach to reduce the complexity of the rotor head is to control yaw by differential changing of the rotor angular velocities. By increasing the airspeed, the induced drag increases, too. In order to hold the flight level, the rotor velocity of one rotor has to decrease while the other rotor increases its velocity. Since changing the rotor speed by full scale helicopters takes too much time, this method is mainly used in small model and toy helicopters. In order to avoid unintended rotation around the z axis, most of the coaxial model helicopters are equipped with a gyro. A drawback of this configuration is that this kind of coaxial helicopters needs a separate actuator for each rotor.

There are a lot of other solutions for yaw control of helicopters. The required torque to turn the helicopter can be provided by a tail rotor, yaw paddles[4], a ducted fan or an air jet configuration. Since these variants for yaw control are not specific for coaxial helicopters, they are not given a closer look in this work.

2.3 Pitch and Roll Control

Independent from the helicopter type, there are two main types to control pitch and roll. Movements ahead and sidewards are possible either by inducing cyclic pitch to the swashplate or by tilting the whole rotor head in the desired direction. Full scale helicopters normally use the cyclic pitch variant. This method needs less force compared to tilting the rotor, since the steering is supported by the self-oscillation of the rotor blades. The benefit of tilting the rotor is that no cyclic pitch is necessary, which reduces the complexity of the swashplate. Since a much higher force is needed to tilt rotor compared to cyclic pitch control, such helicopter configurations are only practicable in small and lightweight helicopters.

As an alternative concept, additional actuators like propellers are used to produce force and movement in x and y direction. When these additional actuators are fixed laterally displaced, they may also be used for yaw control.

2.4 Complete Solutions

The mentioned variants for altitude, yaw, pitch and roll control of coaxial helicopters are listed in Table 2.1. For the control of coaxial helicopters these variants are combined. The most reasonable combinations are described more precisely in this section.

Table 2.1: Control mechanism.

altitude control	**yaw control**	**pitch and roll control**
rotor angular velocity	differential collective pitch	cyclic pitch
blade surface	differential rotor angular velocity	tilt rotor
angle of attack	tail rotor	additional actuator
	ducted fan	
	yaw paddles	

2.4.1 The Kamov Concept

The Kamov Company has built most full scale coaxial helicopters so far. The rotor heads of their helicopters comprise one swashplate for each rotor disc. The two swashplates are connected with the rotor blades and between each other with linking rods. Figure 2.3 shows such a typical Kamov rotor head. Due to the counterrotating rotor discs, the coaxial rotor head is a more complex mechanical

[4]tiltable paddles in the rotor downwind to induce yaw torque

construction than the rotor head of helicopters with only one main rotor. Both swashplates can be moved up- and downwards independently. With this capability, yaw control is possible without changing the produced thrust. This is done by increasing the collective pitch of one rotor and decreasing the collective pitch of the other rotor. Due to increasing drag by higher pitch angles, there is no longer a torque balance. As a result, the helicopter begins to turn around the z axis. In order to get a movement in the x or y direction, cyclic pitch is induced by the two swashplates. Because of the phase shift, the two swashplates are no longer parallel. The handling with the phase shift makes the rotor head more complex than it already is. For movements in z direction, both swashplates induce proportional higher or lower collective pitch to their rotor discs. In this way, the thrust vector in z direction increases or decreases and the helicopter begins to climb or sink.

Figure 2.3: The rotor head of a Kamov Ka-32A12 [6].

2.4.2 Other Concepts

Another idea to reduce the complexity of the rotor head for a coaxial helicopter is described in Eugene F. Rock's [7] invention. Figure 2.4 (left) shows a sketch of this invention. In Rock's patent, the concept of a coaxial helicopter is simplified by using only one swashplate. This swashplate provides the pitch and roll control. In the patent, different possibilities for collective pitch are given. Collective pitch is possible on both, on one or on none of the two rotors. The two counterrotating rotors are mounted on two shafts which are powered by one actuator. The usage of only one actuator yields that the rotor angle velocity Ω is not changeable for each rotor separately. As a consequence altitude control is done by changing the airspeed or by giving more collective pitch to the rotors. In order to control yaw different collective pitch, yaw paddles (airfoils in the rotor downwash), a tail rotor, a ducted fan or an air jet configuration are described. Table 2.2 shows a survey over the mentioned variants in Rock's patent.

Table 2.2: Control variants in Rock's patent

NR	Cyclic	Collective	Yaw control
1a	lower	none	yaw paddles
1b	lower	lower	yaw paddles
2a	lower	both proportional	yaw paddles
2b	lower	both differential	differential collective
3	upper	none	yaw paddles
4	upper	both prop. and diff.	differential collective
5	upper	upper	

The column "Cyclic" shows on which rotor disc cyclic pitch is provided. The column "Collective" shows the different possibilities for collective pitch. The expression "both proportional" means that both rotor discs are changeable in their collective pitch but only proportional. The expression "both differential" means that both rotor discs are changeable in their collective pitch but in opposite direction of each other.

A drawback of most of these variants is that an additional element for yaw control is used. The mentioned yaw paddles are placed in the rotor downwash. In order to yaw, a servo actuator tilts the airfoils. The tilted airfoils induce the desired yaw torque but also an unwanted pitch moment is induced. The variant Nr 4 is able to control yaw without these drawbacks. The assumed advantage of this configuration is negligible because this configuration needs differential collective. This yields to a complex rotor head which is similar to those of the Kamov concept. This way the desired simplification in the rotor head construction does not occur in this variant.

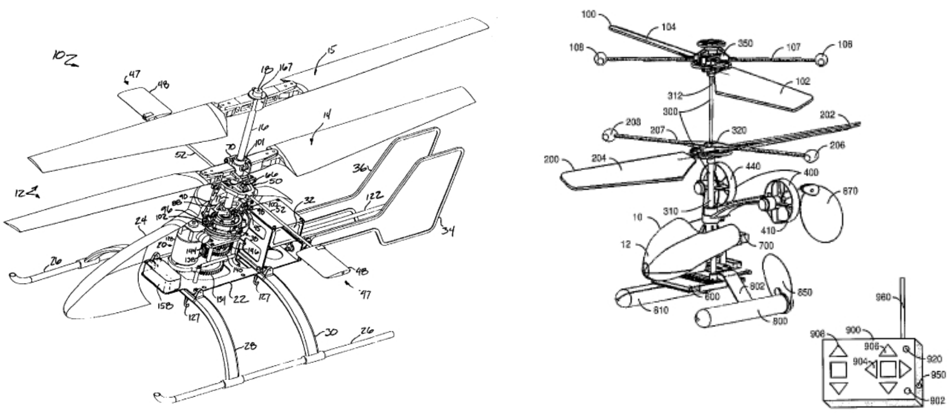


Figure 2.4: Sketches of Rock's patent (left) [7] and the rotary-wing vehicle system with its controller (right) [8].

Another approach for a coaxial concept is described in the WO Patent of Nachman Zimet and Avner Divon [8]. The intention of these two inventors is the development of pitch and roll stable and cheap flight object for the toy market. Their rotary-wing vehicle system consists of two counterrotating rotors. The rotors are not controlled by a swashplate. They are connected with stabilizer bars, which secure aeronautical stability. Since the main rotors are not controllable, additional propellers are added in order to move the vehicle. Figure 2.4 (right) shows a sketch of this vehicle. The control of the vehicle is not helicopter typical, it is more a "tank-like" differential steering. This simplicity yields to a not helicopter specific flight behaviour.

In the patent of an ultralight coaxial rotor aircraft [9], another coaxial concept is described. The mentioned helicopter tilts its rotor in order to control pitch and roll. The rotor heads are simple compared to the rotor heads used for the Kamov concept. Since there is no collective pitch, no swashplate is necessary. A motor actuates the two rotors over a belt drive. Since it is only intended to fly near ground, the altitude control has not to be very fast. The control of the altitude is done by varying the rotor angular velocity. In order to control yaw, a tiltable airfoil is placed in the rotor downwash. Since more power is necessary to control pitch and roll with a tilt rotor instead of a swashplate, this concept is only applicable in relatively small helicopters. Figure 2.5 shows a sketch of this coaxial concept.

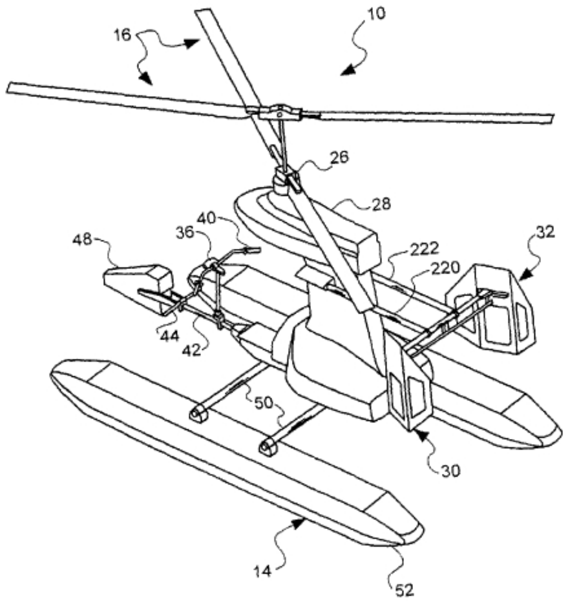


Figure 2.5: A sketch of the ultralight coaxial rotor aircraft [9].

In the Chinese patent [10], a remote controlled (RC) helicopter is described. It consists of two direct current (DC) motors which actuate separately the two rotors. In order to control yaw, different rotor angular velocities are chosen for the two rotors. The pitch and roll control is done with a swashplate for the lower rotor. The upper rotor is not linked to the swashplate but stabilized with a fly bar. Figure 2.6 (left) shows a sketch of this coaxial helicopter concept. This configuration or similar ones are commonly used in coaxial RC helicopters. Figure 2.6 (right) shows such a toy helicopter.

The flybar of the toy helicopter is placed over the upper rotor in contrast to the other one described in the Chinese patent. In general, both configurations fulfil the same task. They give additional stability to the helicopter. In addition to this, the helicopter always hovers over a specified place when no control inputs are given. These properties ensure a simple flight control and provide the possibility of flight manoeuvres on small areas.

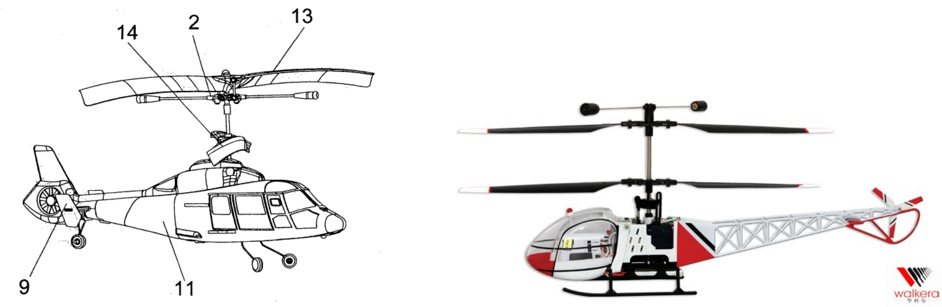


Figure 2.6: A sketch of the remote control helicopter (left) [10] and an image of a common toy RC helicopter (right) [11].

2.4.3 Comparison of Different Coaxial Concepts

As far as the different coaxial concepts are concerned, there are two complete solutions which are widely used today. The first one is the Kamov concept. In the full scale coaxial helicopter flight, there are now other solutions with similar properties. A helicopter with the Kamov concept is controllable in altitude, yaw, pitch and roll with only one actuator. The usage of cyclic and collective pitch on both rotors provides high manoeuvrability. The absence of a long tail rotor gives the possibility of a very compact design. This is a benefit which is important on places where space is rare, such as naval applications. Figure 2.7 shows a KA-25 with a total length of 9.75m and a rotor diameter of 15.74m. A drawback of this configuration compared to other complete solutions is the complexity of the rotor head.

Figure 2.7: A Kamov KA-25 landing on a carrier [12].

In RC helicopter flight, this problem is solved by the usage of only one swashplate which provides pitch and roll control. This complete solution is the second one which is often used today. Since yaw and altitude control is done with the rotor angular velocity, this kind of coaxial helicopters is able to fly without additional control elements like a tail rotor or yaw paddles. A further benefit of this RC helicopter concept is the added stability, which occurs from the usage of a stabilizer bar for the upper rotor.

All other mentioned complete solutions do not have such good capabilities like the Kamov or the RC concept. For the concept with tiltable rotors, there may be a field of application between the full scale and the RC helicopter flight.

Chapter 3

Comparison of Different Rotor Configurations

In this chapter, other rotor configurations than the coaxial configuration are described with their benefits and drawbacks. A closer look is given at the differences between the conventional and the coaxial configuration.

3.1 The Conventional Rotor Configuration

The most common helicopter configuration consists of one main rotor and one tail rotor mounted on the tail boom of the helicopter. In Figure 3.1, a sketch (left) and an example (right) for the conventional rotor configuration are shown.

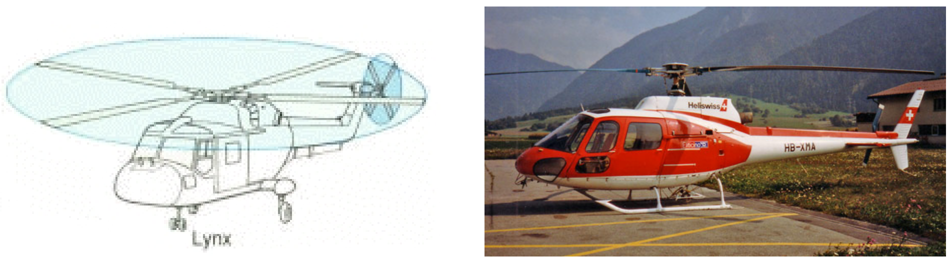


Figure 3.1: Sketch of a conventional helicopter (left) [1] and an image of an Eurocopter AS350B (right) [3].

The tail rotor has to compensate the induced torque of the main rotor. The needed thrust for the tail rotor is inversely proportional to its distance to the centre of gravity of the helicopter. With a long tail boom, the needed power for the tail rotor decreases, which reduces also the consumed power. In order to control yaw, the collective pitch of the tail rotor is varied. This yields to a torque imbalance and the helicopter begins to turn around its z axis. A point that has to be considered is that the tail rotor does not only balance the torque. Its produced thrust results in a force along the y axis, which occurs a sidewards drift of the helicopter. In order to hover, this drift has to be compensated by a small roll angle in the opposite direction of the drift force.

The tail rotor is the main reason for accidents on ground. Since it rotates on the same level where passengers board, there is a risk of injuries caused by contacts with the tail rotor. Furthermore, the interferences of the main and tail rotor generate a big part of the produced noise of the helicopter. In order to avoid these drawbacks, there are alternative torque balance principles. One of these principles is the NOTAR (NO TAil Rotor) system, which uses the coandâ effect and an air jet in order to control yaw. Figure 3.2 shows a sketch of the NOTAR system.

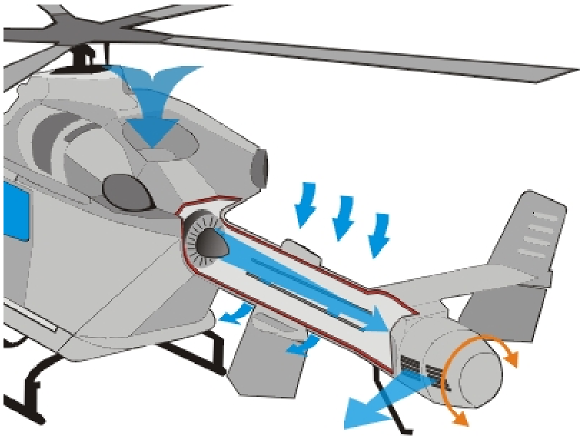


Figure 3.2: The principle of the NOTAR system [3].

A further approach of a conventional helicopter design without using a tail rotor is the usage of tip jet actuation. The tips can be actuated by additional motors on the tips or by thrusting out compressed air through nozzles. This kind of actuation induces no torque to the helicopter, so no tail rotor is needed. The high noise emission and fuel consumption make this concept unsuccesful and only one tip jet helicopter has gone in series production.

3.2 The Tandem Rotor Configuration

The tandem rotor configuration is normally used on large cargo helicopters. It consists of two main rotor systems, mounted on each end of the fuselage. In Figure 3.1, a sketch (left) and an example (right) for the tandem rotor configuration are shown.

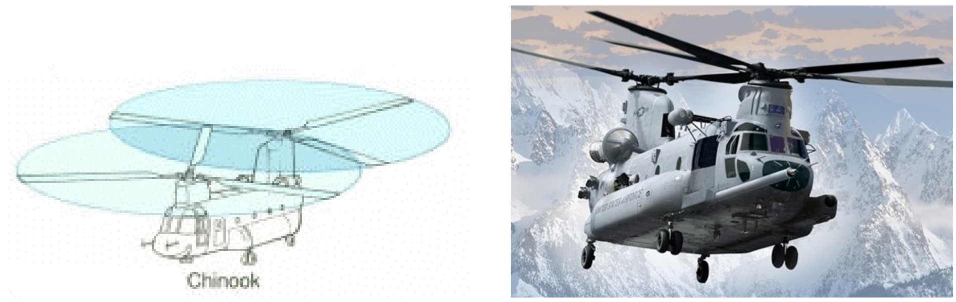


Figure 3.3: Sketch of a tandem helicopter (left) [1] and an image of a Boeing HH-47 CSAR-X (right) [1].

Both rotors operate similarly as the main rotor of the single-rotor helicopter, but they are counterrotating with respect to each other. The counterrotating rotors compensate the induced torque, so a tail rotor is not necessary. As a result, the full engine power can be used for lift. As shown in Figure 3.3 (left), the two rotors use parts of the same area. So as not to collide, the two rotors are linked by a load transmission that ensures a synchronisation of the rotors. This synchronisation guarantees that the two rotors do not hit each other, even during an engine failure.

The relatively big distance between the two rotors makes the load transmission complex and heavy. A further disadvantage is the high drag due to the helicopter's shape. Advantages of the tandem-rotor system are a large centre-of-gravity range and a good longitudinal stability.

3.3 The Intermeshing Rotor Configuration

The intermeshing configuration consists of two main rotors, mounted near together in a V-position. In Figure 3.4 a sketch (left) and an example (right) for the intermeshing rotor configuration are shown. The most known developer of intermeshing helicopters is the Kaman Corporation, which built the first gas turbine helicopter in 1951.

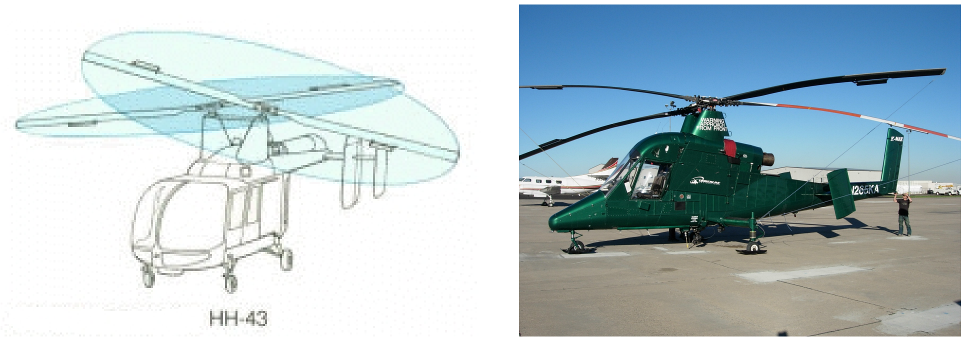


Figure 3.4: Sketch of an intermeshing helicopter (left) [1] and an image of a Kaman K-1200 (right) [13].

Similar to the coaxial and the tandem rotor configuration, the two rotors are counterrotating. Therefore, no tail rotor for the torque compensation is needed. The helicopter is controlled by swashplates similar to the conventional rotor configuration. The V alignment secures that the rotor blades turn over the rotor head of the other rotor. Furthermore, the two rotors are linked by a load transmission that ensures a synchronisation of the rotors. The intermeshing configuration has a space saving configuration of the motor and the gearbox in comparison to the tandem configuration. Compared to the coaxial configuration, the rotor head is less complex. A drawback is that the tips of the rotor blades are near ground on the side of the helicopter. In order to have enough ground clearance, the rotors have to be mounted in a relatively high position. Intermeshing helicopters are mostly used in cargo applications. In general, they have a similar application area like coaxial and tandem helicopters.

3.4 Other Rotor Configurations

Another possible rotor configuration is to place the rotors in parallel. Figure 3.5 shows a sketch (left) of this rotor configuration.

Today, this rotor configuration is seldomly used, but it was important in history. In the years 1937 and 1938, the Focke-Achgelis Fa 61 achieved the helicopter record flight in distance, flight level and flight time. Another important helicopter with the parallel configuration is the Soviet made Mil V-12 shown in Figure 3.5 (right), which is the largest helicopter ever built. However, it never went in production and only prototypes have been built. The Mil V-12 has a total length of 37m and is able to transport more than 20 tonnes.

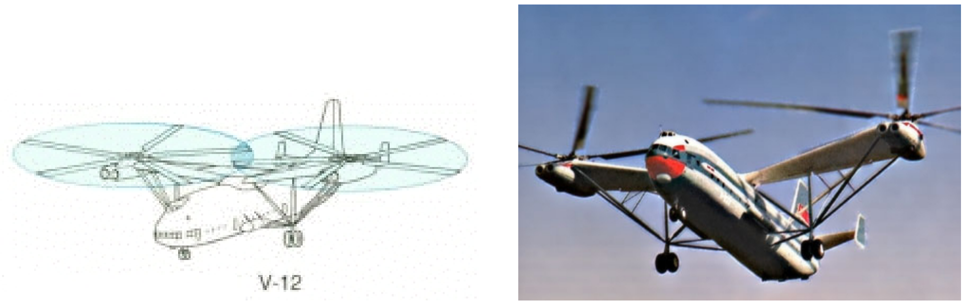


Figure 3.5: Sketch of a parallel helicopter (left) [1] and an image of a Mil V-12 (right) [14].

A rotor configuration mainly used for UAVs is the quadrocopter. It consists of four separately controlled rotors. Quadrocopters are able to control altitude, pitch, roll and yaw only with different thrusts of the rotors. These thrust manipulations can be done by different rotor angular velocities or different collective pitch. With the usage of speed controlled rotors, there is no need for swashplates.

Figure 3.6: A radio controlled quadrocopter [15].

3.5 The Coaxial Configuration Compared to the Conventional Configuration

Today, most helicopters use the conventional rotor configuration. In this section, the benefits and drawbacks of the coaxial rotor configuration compared to the conventional rotor configuration are described.

3.5.1 Steering and Flight Control

The control for pitch, roll and altitude is done in the same way for both rotor configurations. Since the steering inputs of a coaxial helicopter have to be transferred from the lower to the upper swashplate, the rotor head is built more complexly than the rotor head of a conventional helicopter. The maintenance of the rotor head and the gearbox are important expense factors in the usage of helicopters. This is why a coaxial helicopter has normally higher costs of operation than a similar conventional helicopter.

Coaxial helicopters have advantages in yaw control. Compared to conventional helicopters, no tail is rotor needed. As a result, no drift occurs and the complete power can be used for thrust. In contrast to this, conventional helicopters use 5 to 20% of the engine power for yaw control. An unwanted effect which may occur for conventional helicopters is the loss of tail rotor effectiveness. This effect may take place on low velocities caused by a tail vortex ring state or stall. These two factors also limit the maximum yaw velocity for conventional helicopters. Since coaxial helicopters control yaw with their main rotors, these problems are not relevant for them. Furthermore, the abandonment of a long tail boom makes coaxial helicopters more compact. This yields to a smaller inertia which gives higher manoeuvrability. In order to have an accurate longitudinal stability, a small tail boom with a vertical and a horizontal tail are necessary. The smaller length compared to conventional helicopters makes them the preferred solution in areas where space is at a premium like naval roles or in military. The smaller silhouette of coaxial helicopters is a benefit in military applications. Moreover, the usage of no tail rotor makes coaxial helicopters more quiet than conventional helicopters.

3.5.2 Dissymmetry of Lift

When a conventional helicopter is in forward flight, a phenomenon called dissymmetry of lift manifests. This phenomen possesses the potential to disrupt flight stability at high speeds. In Figure 3.7, the superposition of the rotor velocity and the forward flight velocity are shown. The forward moving blade has a higher airspeed than the backward moving blade. This yields to the mentioned dissymmetry of lift. At high enough forward speeds, the backward moving blade has a velocity which decreases with higher radius and may go up to negative speeds on its tip. In such a flight configuration, stall occurs and the helicopter may become uncontrollable. On the other side, the forward moving rotor blade travels through the air sufficiently quickly for the airflow over it to become transonic or even supersonic, which causes fundamental changes in the airflow over the rotor blades. As a fact of these two effects producing the dissymmetry of lift, an upper speed limit for conventional helicopters known as the Never-Exceed Speed V_{NE} is set.

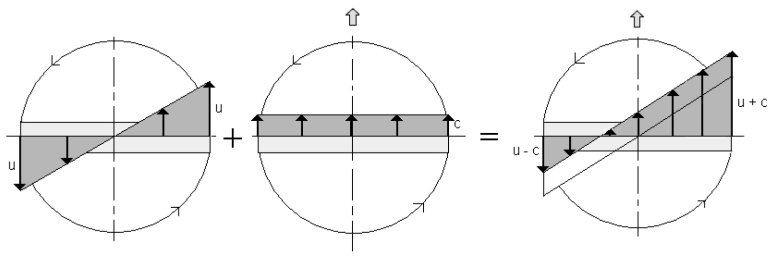


Figure 3.7: The effect of flight speed to the blade velocities [16].

For coaxial rotors, the problem of dissymmetry of lift does not exist. Since the rotors are counterrotating, the lift loss on the lower rotor on one side is compensated by the increased lift on the same side of the upper rotor. As a consequence, coaxial helicopters theoretically can fly faster than conventional helicopters. Furthermore, coaxial helicopters are more stable in extreme flight situations because the resulting thrust force is always central over the rotor head. However, a maximum speed also exists for coaxial helicopters, since the problems arising from rotor tips entering the supersonic aerodynamic sector still apply. The high drag occurred from the sonic barrier defines a V_{NE} for coaxial helicopters as well.

3.5.3 Rotor Thrust

In order to compare different rotor configurations, different coefficients are necessary. Equation 3.1 shows the thrust C_T and the torque coefficient C_Q. Sometimes, the power coefficient C_P is used, which is identical to the torque coefficient. A further coefficient is the solidity σ, which defines the blade area divided by the area of the rotor disc. The used variables are the density of the air (ρ), the rotor radius R, the angular velocity Ω, the number of blades b and the chord length c of the rotor blades . The figure of merit FOM is defined as the ratio of the ideal power required to the actual power required.

$$C_\mathrm{T} = \frac{\text{Rotor thrust}}{\rho(\Omega R)^2 \pi R^2} \quad C_\mathrm{Q} = \frac{\text{Rotor torque}}{\rho(\Omega R)^2 \pi R^2 R} \quad \sigma = \frac{bc}{\pi R} \quad \mathrm{FOM} = \frac{C_\mathrm{T}^{3/2}}{\sqrt{2} C_\mathrm{Q}} \tag{3.1}$$

A first approach to test the performance of multirotor configuration is done by Richard C. Dingeldein [17]. In his experiment, a coaxial rotor with a total of four rotor blades is compared to a single rotor with two blades. The diameters of the two configurations are not identical. The result of these experiments shows that up to 14% more power is needed for the coaxial configuration for the same conditions.

In order to receive a suitable comparison, the coaxial and the conventional rotor should have the same number of blades and the blades of the two systems should be geometrically identical. This yields of course to the same solidity σ for the two rotor configurations. In [18], calculations with these constraints are described. The vorticity transport model has been used to compare the different rotor configurations. Figure 3.8 (left) shows that the coaxial configuration needs less power to create the same thrust like the conventional configuration. Figure 3.8 (right) shows that the benefit of the coaxial configuration decreases with higher forward speed. At advance ratios[1] higher than 0.2, the performance of the two configurations is nearly identical.

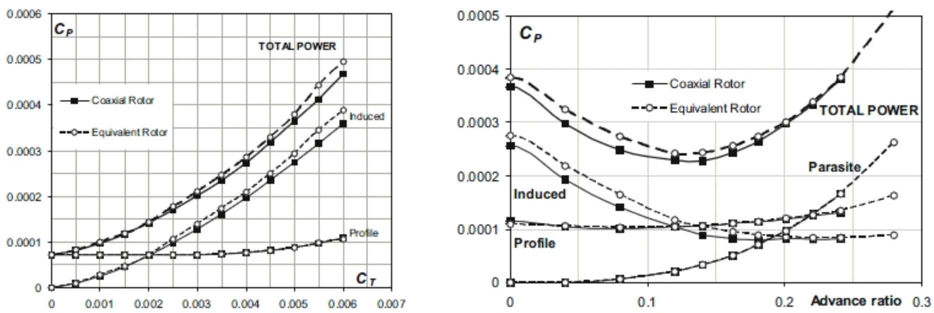


Figure 3.8: The power consumption in hover as a function of thrust (left) and the power consumption in steady level flight as a function of advance ratio (right) [18].

In [19], an explanation for the better performance in hovering of coaxial rotors is given. The lower rotor draws in additional clean air. Figure 3.9 shows the effective increase of the coaxial rotor disc area. This extra clean air and a reduction of the swirl in the wake yield to a better performance of the coaxial rotor compared to the conventional one. The Kamov Company estimates that coaxial rotor helicopters have an overall efficiency 17% to 30% higher than single rotor helicopters.

[1] The ratio of forward flight speed to the speed of the rotor tip of a helicopter

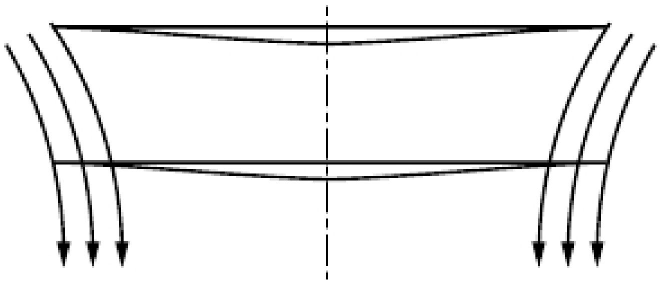


Figure 3.9: The clean air drawn in by the lower rotor [19].

In order to improve the performance of the coaxial rotor design, further modifications are tested. One of them is the reduction of the upper rotor radius. Since the induced power increases for the upper rotor while the performance increases for the lower rotor due to drawn in fresh air, a suitable trade off has to be detected. In [19] the most promising results are obtained for an 8% reduction in the upper rotor radius. Further modifications are done in the rotor spacings. As a result, it is shown that rotor spacings higher than a twentieth part of the rotor diameter have only an insignificant influence on the performance, only the distribution of the thrust is mentionably affected by different rotor spacings. In full scale helicopter flight the rotor spacing is usually chosen around a tenth part of the rotor diameter. In coaxial UAVs the rotor space is normally higher.

As mentioned, the lower rotor works in the downwash of the upper rotor. In order to have the same angle of attack, the collective pitch has to be higher on the lower rotor. In hovering, the lower rotor has to have an about 1.5% higher pitch angle than the upper rotor. In [19] it is shown that the best pitch setting concerning the performance always results in torque balance.

The different tests condensed, it is said that coaxial helicopters have a slightly better performance compared to single rotors with the same solidity, number of blades and rotor diameter. In addition to this, the conventional design needs additional power in order to actuate the tail rotor. This results on a better utilisation of the produced power for coaxial helicopters compared to conventional helicopters.

Chapter 4

The Evolution of Coaxial Helicopters

The first approaches in helicopter design were made in 1493 by Leonardo Da Vinci. His helicopter studies, called the "airscrew", consist of a platform with a helical screw driven by a primitive actuator system. The "airscrew" and later developments in coaxial helicopter history are shown in a timeline in Figure 4.1. Since the description of the complete helicopter history is too extensive for this paper, only the most relevant coaxial developments are mentioned.

In the 18th century, new developments were made by Lomonosov and Launoy & Bienvenu. Up to the beginning of the 20th century a lot of other approaches were made. Due to the lack of an accurate actuator system concerning the power to weight ratio, no built helicopters were able to lift humans. With the invention of the gas engine in 1885, the base for successful helicopter flight with respect to actuation was given. However, it took more than another 20 years until the first helicopter became airborne. The first man carrying helicopter flight to a flight level of about 60cm was made in autumn 1907 with the "Breguet-Richet Gyroplane No.1". This helicopter consisted of a total of four rotor pairs.

In Russia, a lot of inventors worked on the development of coaxial helicopters. I.I.Sikorsky and K.A.Antonov developed coaxial prototypes in 1909 and 1910. However, they were not able to fly. During the first world war, no mentionable developments concerning coaxial helicopters were made. The next successful approach was done by Pateras Pescara. His coaxial helicopter "Pescara No.3" was able to fly longer than five minutes and reached a maximum speed of 12 km/h. Pescara was in a permanent competition with Etienne Oemichen. Both made several FAI flight records. A further progress was done in 1930 by Corridion D'Ascanio. His flight vehicle consisted of counterrotating coaxial rotors which were variable in the rotor blade angle of attack. The vehicle set three FAI records. It reached an altitude of 18m, covered a distance of 1078m and flew longer than eight minutes. Five years later the "Gyroplane" was built by Louis Breguet. This helicopter was the first really successful helicopter. Equipped with collective and cyclic pitch control, it was able to control pitch, roll and yaw with its two coaxial main rotors. The"Gyroplane" flew at 107km/h, climbed to an altitude of 158m, and remained in the air for more than one hour.

In Russia, the later main developer of coaxial helicopters Nikolai I. Kamov built autogyros in the 1930s and 1940s . The idea of the autogyro with an autorotating rotor came to the Spanish engineer Juan de la Cierva. The properties of the autogyro place it in an intermediate position between the aeroplane and the helicopter. Since autogyros were easier to build and more safe than helicopters at this time, they were very successful in the 1930s and 1940s.

The rise of the Kamov Company began in 1947 with the “Kamov Ka-8”. This simple coaxial helicopter was like a flying motorcycle. Its follower the “Kamov Ka-10” was built in 1949 and had better flight characteristics and reliability. In 1953 the “Kamov KA-15” was built. This helicopter was often used for naval applications. The success of the “Kamov Ka-15” and the former variants yield to the result that the Kamov Company became the most important developer of coaxial helicopters up to the present. A selection of the most important further coaxial developments is shown in Figure 4.2.

An important step from the full scale helicopters to UAVs and MAVs is the development of the “Kamov Ka-37” and other UAVs. The unmanned coaxial helicopter was developed by Daewoo in 1993 and is able to transport 50 kg by a flight time of 45 minutes and a cruise speed of 110km/h. However, there were UAVs already used some years earlier for example the Gyrodyne “QH-50”. The first radio controlled helicopters were built in the ’70s. Up to now fast improvements have been made, and the expensive and unreliable RC helicopters have become affordable in the last years. At present, there is a broad assortment of RC helicopters in the toy market as well as in industrial applications.

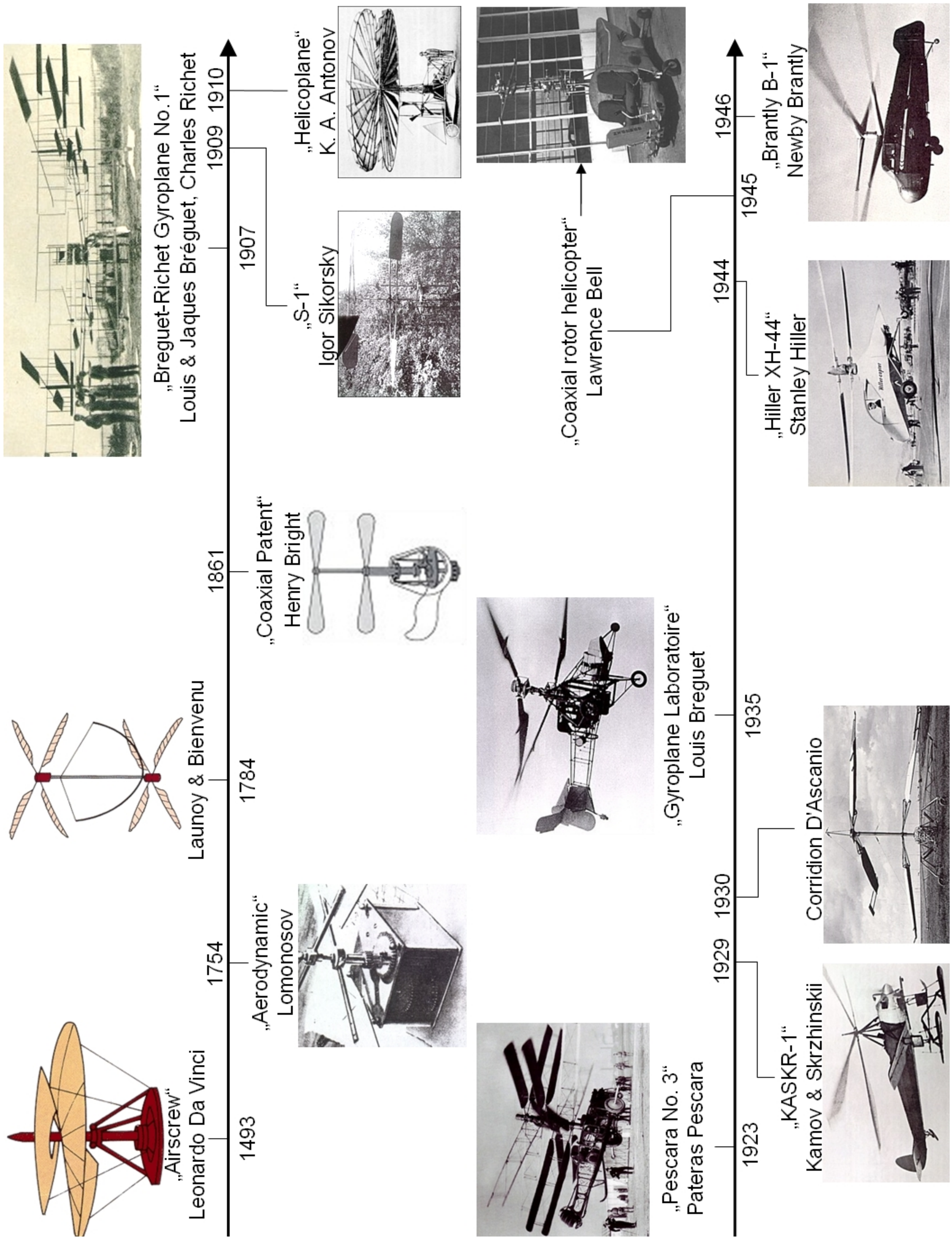


Figure 4.1: The evolution of coaxial helicopters from the beginning to 1946.

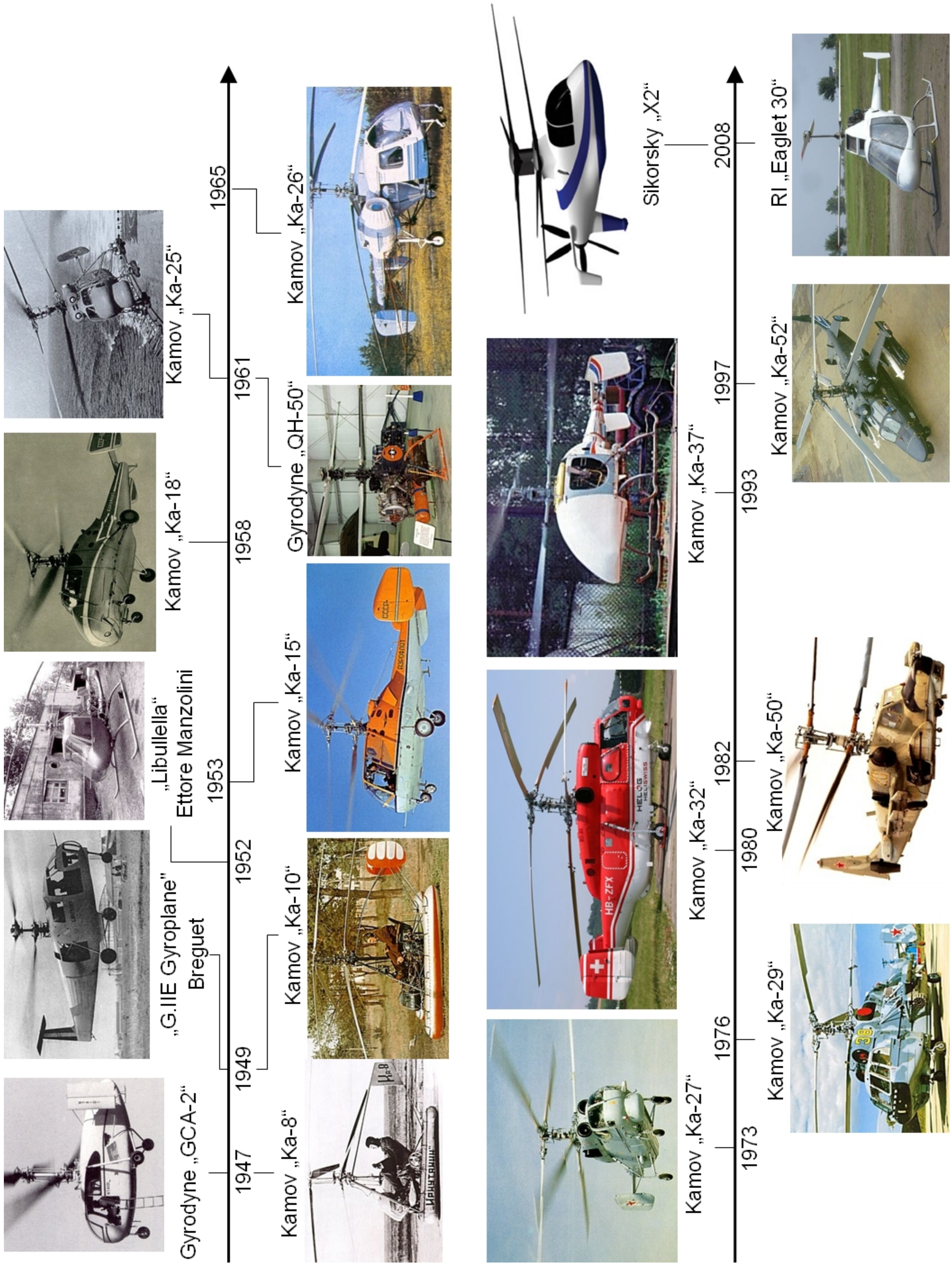


Figure 4.2: The evolution of coaxial helicopters from 1947 to 2009.

Chapter 5

Conclusion and Outlook

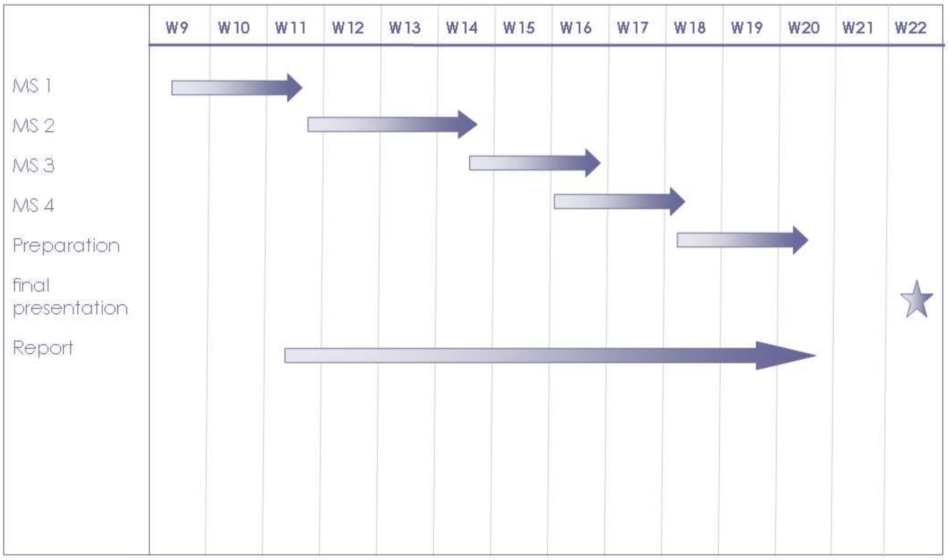
In present applications, there are two mainly used coaxial concepts. In full scale helicopter flight, the Kamov concept is used. Compared to conventional helicopters, the benefits are a higher manoeuvrability and more compact design which makes coaxial helicopters to the preferred design in applications where space is an important factor. Furthermore, coaxial helicopters use the whole power for thrust, whereas conventional helicopters need some power (up to 20%) to actuate the tail rotor. The main drawback of coaxial helicopters is the high complexity of the rotor head. This yields to high maintenance costs. This financial aspect is may the most important for the rare usage of coaxial helicopters in full scale helicopter flight.

In the UAV area, the maintenance and the complexity of coaxial rotor heads are not highly important factors. A big benefit of coaxial rotors is that no drift is produced. With the usage of only one swashplate and only cyclic pitch on the lower rotor and a stabilized upper rotor, the coaxial concept has a similar complexity like conventional helicopters. The loss of flight performance concerning the maximum speed is not relevant since a stable hovering is much more important for UAVs. The higher stability and the fact that the whole power is used for thrust are crucial criteria for the widely usage in the MAV area.

As mentioned, the big disadvantage of coaxial helicopters is the complexity of the rotor head. In order to reduce this complexity, different modifications are possible. A German-Russian cooperation [21] builds coaxial helicopters with hingeless blade mounts. A future development is the usage of fly-by-wire technique. This means that the mechanical connections are replaced by electrical components. These replacements reduce the complexity of the swashplate and as a result the maintenance costs drop. In order to abstain completely from swashplates, further technical developments are necessary. An approach is the usage of electrically changeable blade adjusting rods. This concept, called individual blade control (IBC), is developed by the "Fa. ZF Luftfahrttechnik Calden". The IBC is able to elongate and contract during a rotation and induces cyclic and collective pitch controlled with electrical inputs. The IBC system is in a prototype state and may become important in future helicopter applications. With the usage of this system, the main disadvantage of coaxial helicopters is eliminated. As a result, coaxial helicopters may become more common in future full scale helicopter flight.

Appendix A

Timetable



- **Datas:**
- Spring Semester 2009: 16.02.2009 – 29.05.2009
- Final presentation: 24-27 May (Week 22)
- Each Monday: Meeting 3 pm

- **Description:**
- MS1: Collection of appropriate literature (books, papers, webpages)
- MS2: Description of different coaxial concepts with respect to steering and altitude control
- MS3: Comparison of the coaxial helicopter with other rotor configurations
- MS4: Illustration of the evolution of coaxial helicopter in a timeline
- Preparation: Prepare the oral presentation
- Report: Reporting and documentation will be done during the whole studies

- **My timetable**
- Tue 13-17 Electrical Drive Systems I
- Thu 8-10 Digital Control Systems

Appendix B

Announcement

ETH

Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Autonomous Systems Lab
Prof. Dr. Roland Siegwart

SoM: From Kamov's first design to Micro Aerial Vehicles – a survey on coaxial helicopters

Kurzbeschreibung / short description

Studies on Mechatronics on the history and evolution of coaxial helicopter design

Typ / type	Studies on Mechatronics
Partner	
Zeitdauer / period	Spring semester 2009
Student(en) / student(s)	
Betreuung intern / internal supervisor	Christian Bermes, bermes@mavt.ethz.ch
Betreuung extern / external supervisor	

Stichworte / key words

Coaxial helicopter, Micro Aerial Vehicle

Umfeld / context

Coaxial helicopters are rather nonstandard in the full scale helicopter domain, while they are widely used as Mini and Micro Aerial Vehicles. We want to have a closer look at the rise of this design, its evolution and its entry into the MAV domain. Since there are some resources available in Russian, profound knowledge of Russian is an advantage (but certainly not a prerequisite!) for prospective students.

Arbeitspakete / work packages

- It is only a project of „Studies on Mechatronics“! Students have to sign up for the Studies on Mechatronics through www.mystudies.ethz.ch . No ASL registration is required; no workplace is provided for this kind of project. Course unit number: 151-0640-00L Studies on Mechatronics (www.vvz.ethz.ch). Workload: 8-9 hours per week (5 credit points). See http://wiki.asl.ethz.ch/index.php/Student_Projects#Studies_on_Mechatronics for more info.
- Work packages
    - Collection of appropriate literature (books, papers, webpages)
    - Description of different coaxial concepts with respect to steering and altitude control
    - Comparison of the coaxial helicopter with other rotor configurations
    - Illustration of the evolution of coaxial helicopters in a timeline



Bibliography

[1] http://www.helis.com
05/04/2009

[2] http://quest.arc.nasa.gov/aero/virtual/demo/aeronautics/tutorial/images/3axis.gif
05/04/2009

[3] http://www.heli.li
05/04/2009

[4] http://en.wikivisual.com/images/0/04/Drag_Curve_2.jpg
05/04/2009

[5] http://wpcontent.answers.com/wikipedia/en/4/42/LiftCurve.gif
05/04/2009

[6] http://www.fotocommunity.de/pc/pc/display/11025754
05/04/2009

[7] Eugene F. Rock: *Coaxial Helicopter*. Airscooter Corporation, United States Patent Application Publication, 2002

[8] Nachman Zimet, Avner Divon: *Rotary-wing vehicle system* . PCT Patent, 2007

[9] Arthur E. Phelps III, Elwood G. Norris, Eugene F. Rock, Emitt Wallace: *Ultralight coaxial rotor aircraft*. Airscooter Corporation, PCT Patent, 2002

[10] Xu Wenyu: *A remote control helicopter*. PCT Patent, 2009

[11] http://www.ehirobo.com/shop/images/heliimage/walkera_5G4.jpg
05/04/2009

[12] http://www.military-today.com/helicopters/kamov_ka25_hormone_l3.jpg
10/05/2009

[13] http://upload.wikimedia.org/wikipedia/en/1/10/N265ka_krj.JPG
10/05/2009

[14] http://www.dmb-ps.co.jp/dmbpilot/Mi-12.jpg
23/05/2009

[15] http://upload.wikimedia.org/wikipedia/commons/f/f6/Xufo3b.jpg
23/05/2009

[16] http://upload.wikimedia.org/wikipedia/de/d/d0/Heli-Anstr..PNG
23/05/2009

[17] Richard C. Dingeldein: *Wind-tunnel Studies of the Performance of Multirotor Configurations.* Langley Aeronautical Laboratory, Washington, 1954

[18] Hyo Won Kim, Richard E. Brown: *Modelling the Aerodynamics of Coaxial Helicopters - from an Isolated Rotor to a Complete Aircraft.* Proceedings of the EU-Korea Conference on Science and Technology, 2008

[19] Colin P. Coleman: *A Survey of Theoretical and Experimental Coaxial Rotor Aerodynamic Research.* National Aeronautics and Space Administration, 1997

[20] http://www.aviastar.org/
23/05/2009

[21] http://www.rotor-international.net
23/05/2009

[22] Robert Jackson: *Hubschrauber Fluschrauber Tragschrauber, Die Gechichte der Drehflügler.* Motorbuch Verlag Stuttgart, 1976

[23] Robert Jackson: *Hubschrauber.* Motorbuch Verlag Stuttgart, 2007

[24] Hans-Joachim Polte: *Hubschrauber : Geschichte, Technik und Einsatz.* Verlag E. S. Mittler & Sohn GmbH, 1986

[25] Giorgio Apostolo: *Enzyklopädie der Hubschrauber.* Weltbildverlag GmbH, 1995

[26] Ulf Gerber: *Die Entwicklung des sowjetischen Hubschrauberbaus.* Elbe-Dnjepr-Verlag, 2002

[27] Rolf Besser: *Technik und Geschichte der Hubschrauber.* Bernaard & Graefe Verlag, 1996

[28] Marcus Aulfinger: *Hubschrauber-Typenbuch.* Motorbuchverlag, 2007

[29] David Hyunchul Shim, Jae-Sup Han, Hong-Tae Yeo: *A Development of Unmanned Helicopters for Industrial Applications.* Springer Science + Business Media B.V., 2008

[30] V. A. Anikin, B. A. Vassiliev, V. N. Kvokov: *Modeling of Coaxial Helicopter Flight Characteristics.* 27th European Rotorcraft Forum, Moscow, Russia, 2001