CHAPTER 3

COAXIAL ROTOR CONFIGURATION

This chapter gives an overview of the development of coaxial rotor configuration. The benefits and drawbacks of this kind of flying vehicle are first introduced. Then, a brief of coaxial helicopter history is presented by summarizing main events in the development of coaxial rotor configuration. Recent and current research projects as well as achievement on development of micro coaxial at several universities and research centers are also included as a main content of this chapter.

3.1 Coaxial helicopter description

A coaxial helicopter is a twin main rotor helicopter configuration that uses two contra-rotating rotors of equal size and loading, driven by two concentric shafts. Some vertical separation between two rotors is required to avoid the rotor's collision due to the lateral flapping.

Figure 3-1 Coaxial helicopter: Kamov Ka-50 (left) and Blade CX (right)

Large coaxial helicopters normally have two engines and gearboxes to drive two rotors in opposite direction, while micro coaxial helicopter can has one, two or multi-rotors to drive at least two main rotors.

A typical coaxial helicopter achieves vertical motion and yaw rotation by simultaneously or differently changing the speed of rotation of each rotor. Longitudinal translation is achieved by tilting the thrust vector through the swash-plate systems on lower rotor or on both rotors. For micro coaxial models, a stabilizer is also included to provide passive control.

3.2 Coaxial rotor benefits and drawbacks

3.2.1 Coaxial rotor benefits

3.2.1.1 Benefit of solving the problem of angular momentum

One of the problems with any helicopter with a single set of rotor blades is the tendency of the helicopter body to begin spinning in the opposite sense to that of the rotors once airborne. To counteract the effect, the tail rotor was introduced to provide a constant input of angular momentum to the body in the opposite direction to that from the rotor. These two same magnitude, opposite direction momentum quantities will cancel each other out. Hence, the condition of zero total angular momentum is maintained. The helicopter's fuselage remains stationary and stable level flight becomes possible. However, the tail rotor thrust also perturb the force equilibrium in the lateral axis, this perturbation is countered by tilting the main rotor laterally.

In a coaxial rotor helicopter, two sets of rotors are turned in opposite direction, allowing the fuselage to maintain zero angular momentum until the pilot varies the angular momentum inputs in a controlled fashion to facilitate turning.

3.2.1.2 Benefit of solving the problem of dissymmetry of lift

During hover, the velocity distribution on single rotor is the same for every angular position of rotor around its rotational circle. When the helicopter is in forward flight at certain velocity, there is a difference in local velocity. One can see from figure 3-2 that the advancing blades of the rotor encounter higher velocity than the retreating blades. The difference is twice the helicopter forward speed [7]. Therefore, a sizable rolling moment would be present in forward flight as a result of the dissymmetry in lift generation, notably for the rigid system. In addition, at high forward speeds, the airflow over the advancing rotor could be supersonic while the retreating side could enter the stall condition, and fail to produce lift. Hence, dissymmetry of lift results in an upper speed limit for single rotor helicopter in forward flight. To reduce the effect of such phenomena, flexible rotor is used instead of rigid ones, this solution was first studied by Cierva and then successful applied to autogyro since 1920's [14].

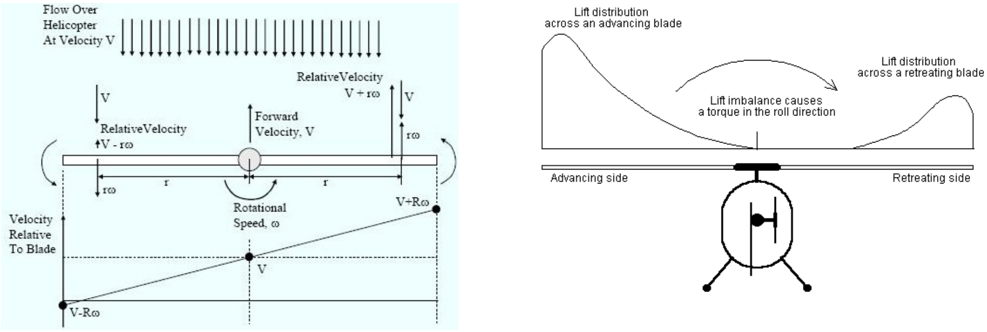

Figure 3-2 Asymmetric of lift and its effect

Coaxial helicopter solve the problem of dissymmetry of lift because any time on either side of the rotor disk, there are an advancing blade and a retreating blade. This makes the lift difference is cancelled out, allowing for higher do-not-exceed speeds that are limited more by engine power and design structural limits than by control issues. The result is that the helicopter is balance in rolling moment and more stable in extreme part of the flight envelope [15].

3.2.1.3 Other benefits

Coaxial helicopter is more compact in airframe structure than conventional single rotor due to the lack of tail rotor. This reduction in size can be up to 30% compared with a single rotor helicopter [7]. As a result, the moment of inertia of the vehicle decreases, which leads to the increase in controllability and maneuverability of the helicopter.

One other benefit arising from a coaxial design is the increased payload for a given engine power. A tail rotor typically wastes some of the power that would otherwise be devoted to lift and thrust. With a coaxial rotor design, all of the available engine power is devoted to lift and thrust. Although interference between coaxial rotors also wastes some of power, but it is much lower than the power saving from the absence of tail rotor. For this reason, the efficiency of coaxial rotor helicopter is generally higher than that of a single rotor helicopter [16].

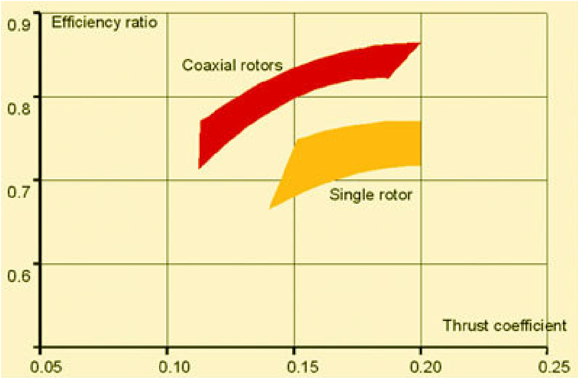

Figure 3-3 Efficiency and thrust coefficient of single and coaxial rotor

3.2.2 Drawbacks of coaxial rotor configuration

The principal drawback of coaxial helicopter design is the increased mechanical complexity of the rotor hub, especially in large coaxial rotor configuration when the swashplate systems are required for both upper and lower rotor. This mission becomes more complicated because of the need to drive two rotor discs in opposite direction.

Other drawbacks are that a certain amount of energy is lost due to the interference effect between two rotors in proximity; weak direction control in forward flight and yaw control force reversed during auto-rotation.

3.3 Coaxial rotor configuration development

History of the development of vertical flight in general or coaxial rotor flight in particular could be remarked based on the development of its technology. Six phases of vertical flight development could be listed as follows:

- Understanding the basic aerodynamics of vertical flight
- Finding solution for lack of power-plant
- Minimizing structure weight and engine weight
- Countering rotor torque reaction
- Providing stability and properly controlling the machine

– Conquering the problem of high vibration

The idea of vertical flight aircraft is believed to root about 400 BC in a toy of Chinese people; a top. This toy as shown in figure 3-3 consisted of feathers at the end of a stick, which rapidly spun between the hands to generated lift and then release into flight [17].

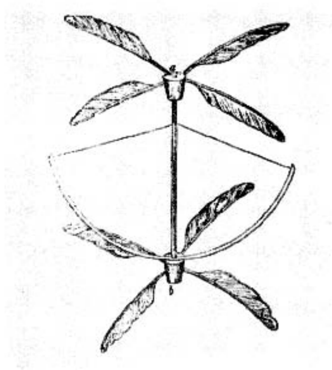

Figure 3-4 Coaxial version of Chinese top

Thousands of years later, in the middle of the 18th century, the Russian scientist Mikhail Lomonosov first proposed the construction of a compact co-axial layout helicopter based on Chinese top, powered by a wound up spring device. The model flew freely and climb to a good altitude.

Until the middle of the 19th century, however, works on contra-rotary rotors were published only sporadically and contained fragmentary information. One of considerable research in this period was the study on aerodynamic force on lifting wings, carried by English scientist George Cayley in the end of 18th century. George had successfully constructed several vertical flight models with small rotors made of sheets of tin, and had also raised the idea about large vertical flight aircraft.

In 1840s, Horatio Phillips, constructed a steam driven vertical flight machine. This event marked the first time that rotary model had flown under the power of an engine rather than stored energy such as wound-up springs [18].

During the period from middle of 18th century to the early of 1900s, there were some attempts to build contra rotary rotors driven by steam engine, such as model of Dieuaide (1877), coaxial model of Enrico Forlamini (1878)[19]. But all of these machines could not lift-off due to underpowered and overweight problem. There was no control systems included in these machines [17].

By the beginning of 1900s, internal combustion engine was invented and had significant contribution to the success of machine flight. Although the S2 coaxial rotor machine with 25hp Anzani engine, developed and tested by Igor Ivanovitch Sikorsky in 1910, could only make short hops, it rose the hope that rotary wing flying machine could be true with better engine and lighter material.

Figure 3-5 S2 coaxial helicopter

Up to decade of 1910s, the emphasis was still entirely on achieved lift, flight control just had a little development with the used of collective pitch for controlling the rotors, concept of cyclic pitch for rotor control had been proposed but not ready for used [17].

About 1914, the Danish pioneer Jens Ellehammer designed and tested a piloted coaxial helicopter. The machine consisted of two rotors with several short blades attached to two large circular aluminum rings; cyclic pitch mechanism was used to provide the control. During the testing, this man-carrying machine could make many short hops into the air but never made a properly controlled free flight. These events bring the conclusion that production of lift as well as control were still problems need to deal with, although some achievement had been obtained.

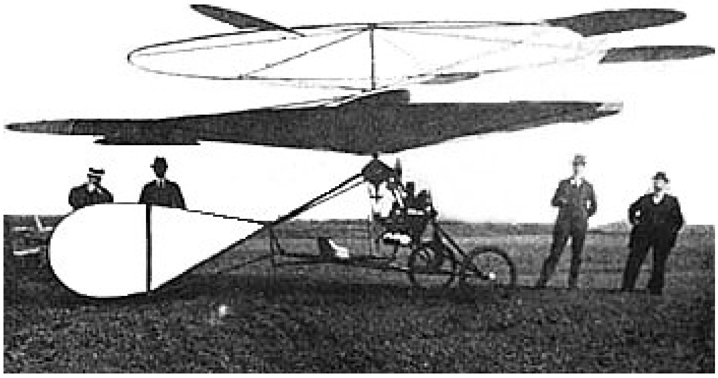

Figure 3-6 Ellehammer coaxial helicopter

Through the decade of 1920s, the development of coaxial helicopter had obvious advance in both practice and theory, remarked with the first hop and semi-control flight.

In the aspect of building and testing, coaxial rotor machine had already the ability of lift-off, reach and at remain at certain altitude and also controllable in pitch and yaw. The event that a counter-rotating coaxial machine developed by Henri Berliner (1919) could make uncontrolled hops into the air, reach a height of about four feet; and the fact that the biplane-type rotors coaxial helicopter built by Raul Pescara could use both cyclic pitch and collective pitch for control were the conclusive evidences of this development.

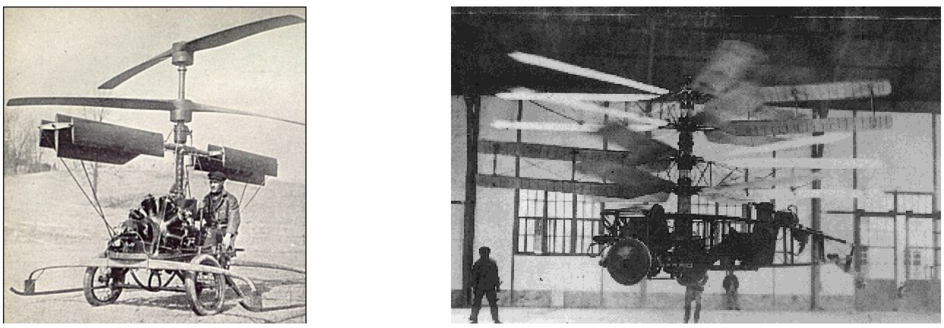

Figure 3-7 Coaxial model of Henri Berliner (left) and Raul Pescara (right)

In the theory aspect, study on rotor performance, power required for vertical flight and countering of rotor torque reaction had been carried out by Theodore von Karman (1921), William F. Durand (1920), Munk (1923) and Juan de la Cierva (1923). Notable in these researches was the study on countering the rotor torque reaction by Juan de la Cierva with the idea of using lower rotor to counteract the asymmetry of lift produced on the upper rotor to balance the rolling moment on the aircraft. Cierva also mentioned that aerodynamic interference produced between rotors resulted in different rotor speed, spoiling the requirement aerodynamic roll balance.

The era of successful flight with fully controlled flight of coaxial helicopter was first remarked by Corradino d'Ascanio in 1930 with his helicopter as shown in figure 3-8.

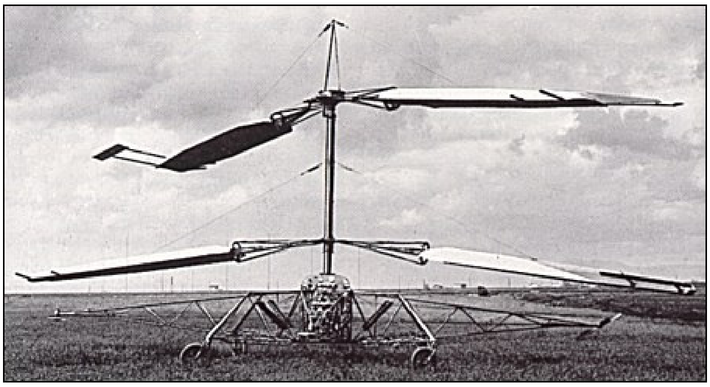

Figure 3-8 Corradino's coaxial helicopter

One can see from figure 3-8 that the machine consists of two large counter-rotating rotors with two blades per each rotor; these blades are connected to the driven shaft by hinges, which allow the blade to flap and feather for changing the blade pitch. Control was achieved by the servo-tabs on the trailing edges of the blades. These tab can be deflected periodically (cyclic pitch) or moved collectively (collective pitch) to give the forward/sideward and vertical control. Three small propellers mounted to the airframe were used for additional pitch, roll and yaw control [17].

A few after the first controllable flight of Corradino d'Ascanio, about 1935 – 1936), Breguet-Dorand had successfully applied the swashplate system for controlling cyclic pitch. The model of Dorand not only had taped blade with flap and lag hinges, but also added with horizontal and vertical tail for increase of stability. Yaw control was achieved by differential torque on one rotor with respect to the other rotor.

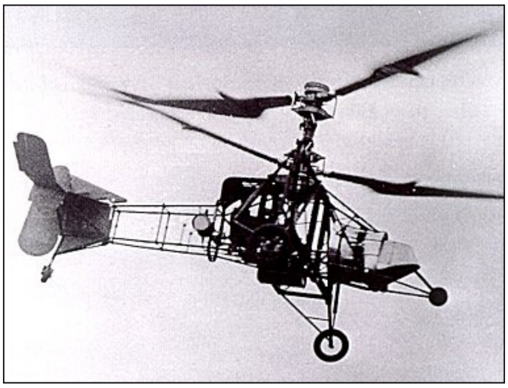

Figure 3-9 Breguet-Dorand coaxial helicopter

The successful of Breguet-Dorand's coaxial helicopter closed the first era of coaxial rotor configuration development, and also opened the new era of this kind of aircraft. Since then, coaxial rotor development got more successes and quickly matured into safe and viable aircraft. Together with conventional main/tail rotor, twin rotor side by side, coaxial helicopters were developed, manufactured and used in both civil and military.

Coaxial helicopter achieved successful flight nearly one decade earlier than the conventional main/tail rotor configuration. Breguet- Dorand coaxial helicopter achieved its first successful flight in 1936, while Sikorsky R4-B helicopter was the first conventional helicopter achieved full controlled flight in 1944. However, because of complex mechanism in control, weak direction control in forward flight, yaw control forces reversed during auto-rotation, coaxial helicopter was not attracted as much attention as conventional helicopter.

3.4 Micro coaxial helicopter

This section, which introduces about micro coaxial helicopter, consists of overview of a typical micro coaxial helicopter; introduction of system simplicity to be applied to micro coaxial helicopter compared with large coaxial helicopter and summary of recent/current researches carried out on this MAV configuration.

3.4.1 Micro coaxial helicopter and its simplicity

In general, micro coaxial helicopter has same features as the large ones; the micro model also uses counter-rotating rotors with one above the others to produce lift to support its weight and payload. Micro coaxial helicopter not only has the basic benefits of coaxial rotor which are: countering reaction torque without the used of tail rotor or corresponding system, solving problem of dissymmetry of lift in forward flight, but also has its own advantages.

Micro coaxial helicopters are usually used for indoor flight. Application in this environment requires that the vehicle should have stable hovering, precise movement as well as safety rather than high speed flight and stunt performance. These features make the systems on micro coaxial helicopter quite simpler than the large one.
Micro coaxial helicopter can use clean electric motors to provide enough power for rotor system; or can use two motors with one for each rotor to avoid the gearbox problem.

Figure 3-10 shows the assembly of blades on the upper rotor of a typical micro coaxial helicopter. Two blades with no linked to any servo are connected to the collar of driven shaft by screws, in which allows blade to lag about screw axis. Stabilizer bar (also called fly bar), which consists of two bob weights attached to each end, is directly linked to the upper rotor through the pitch control linkage so that its rotational plane is paralleled to the upper rotor rotational plane. Since the stabilizer bar was linked and driven at same rpm with the upper rotor, the gyroscopic inertia of the bar would slow the respond of the upper rotor to rapid change in cyclic pitch of the bottom rotor by automatically controlling the cyclic pitch of the upper rotor in an attempt to hold it in current plane of rotation. Hence, increasing the effective damping to disturbance and giving stability to the rotor system.

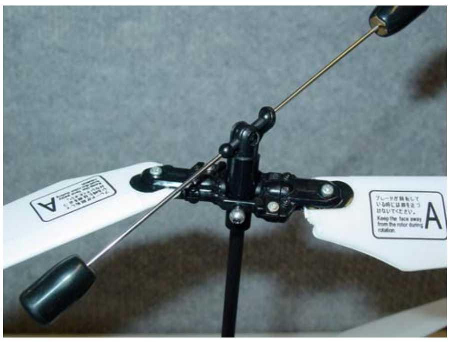

Figure 3-10 Upper rotor assembly

For controlling lower rotor, two servos with linkages to the swasplate system as in figure 3-11 are used; the left servo controls the rotor's lateral cyclic pitch while the right one controls the longitudinal cyclic pitch.

In terms of vertical and yaw control, micro coaxial uses the means of two motors sytem; simultaneous increasing/decreasing of rotor rpm permits increasing/decreasing vehicle altitude; while differing the torque on one rotor with respect to another results in yawing the vehicle.

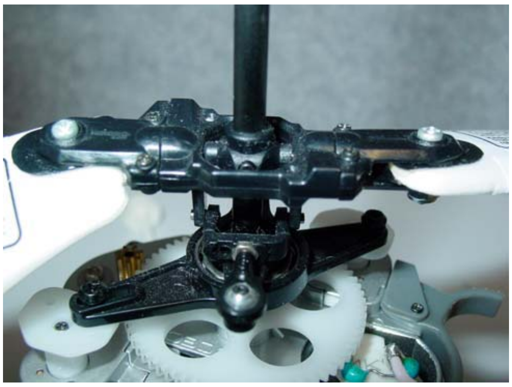

Figure 3-11 Swashplate system and assembly of lower rotor

3.4.2 Recent and current researches carried out on micro coaxial helicopter

Recent year, a number of research groups have been attracted to the topic of development of coaxial rotor for indoor applications. Some projects have focused on studying the dynamic and autonomous control while other has attempted to design and construct the vehicle with innovation. The following subsections give an overview of researches on micro coaxial helicopter at several universities and research centers. Three first subsections concentrates on introducing researches carried out on alternative configurations of micro coaxial helicopter, while the last subsection represents general research on aerodynamic modeling and control.

In general, micro coaxial helicopter can be classified into three small alternative configurations based on the number of motor. Specifically are single motor, dual motors and multi-rotors. Each configuration has specific mechanism as well as control architecture.

3.4.2.1 Single motor micro coaxial helicopter

A group at University of Colorado at Boulder pursued a research on design and construct of Coaxial Hovering Indoor Reconnaissance Probe (CHIRP) [24]. The model as shows in figure 3-12 consisted of two rotors concentric together, driven in opposite direction by using one motor and gear box.

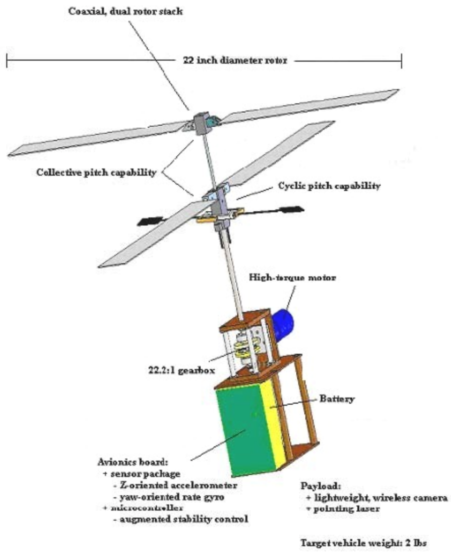

Figure 3-12 CHIRP

An avionics package, composed of accelerometer; yaw-rate gyro; servo multiplexer chip; RC servos and receiver; and flight computer/microcontroller, was used for controlling the model. Mini camera was included onboard of CHIRP to transmit streaming data video image to nearby television.

As the rotor was operated at a constant rate, in order to give the vertical control as well as yaw control, the concept of varying the angle of attack of both upper and lower rotor was introduced by using two collective pitch mechanisms in upper and lower rotor. For control of pitch and roll, longitudinal and lateral motion, cyclic pitch mechanism was attached to the lower rotor.

3.4.2.2 Dual motors micro coaxial helicopter

In this type of micro coaxial helicopter, each rotor is driven by separated motor. During the operation, the rotor rpm can be changed to produce different thrust and torque.

Research at University of Maryland

Figure 3-12 details one of the dual motor coaxial rotors, the MICOR (MIcro Coaxial Rotorcraft) developed at Alfred Gesso Rotorcraft Center (AGRC), University of Maryland.

Figure 3-13 The initial model of MICOR

Initial model of MICOR had two counter rotating rotors with each rotor driven by independent electric motors, which allowed yaw and height control. However, there was no control for the translation motion.

This model then was modified to improve the flight endurance as well as carrying payload, improve lateral control with innovative swashplate. The refine in battery supplied system combined with the changing in rotor configuration made the vehicle could perform a flight of 20 minutes with 20 gram payload.

Another dual motor coaxial rotor developed by AGRC is the model, in which the stability and controllability is increased by using the active flexible structure [25]. The detail of this structure is presented in following figure.

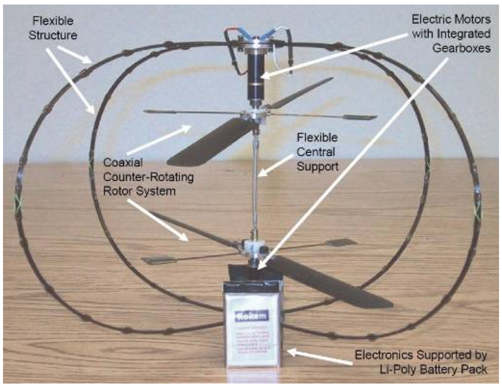

Figure 3-14 Flexible Coaxial MAV

As shows in figure 3-15, the vehicle consists of a set of coaxial, counter-rotating rotors, independently driven by two coaxial electric motors, permitted vertical control by simultaneous changing of rotors' rotational speed. Two stabilizer bars are mounted on each upper and lower rotor. Allowing the rotor to damp small perturbations in the orientation of the vehicle, minimizing the rotor tip path change and giving passive control.

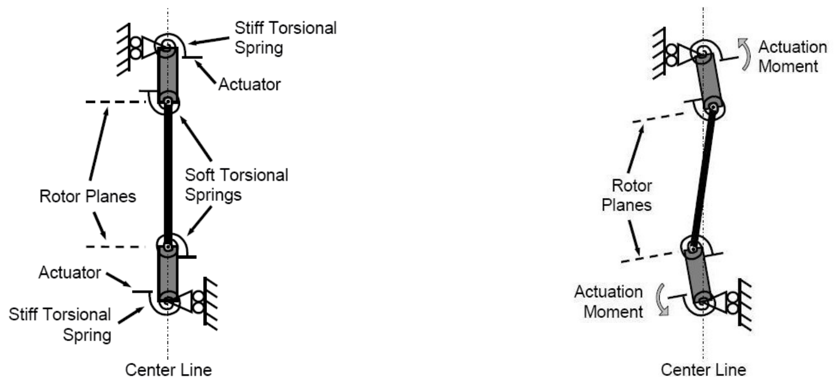

Figure 3-15 Control architecture using flexible structure

Flexible structure consisted of light-weight carbon fiber and shape memory alloy wires are used as solution for vehicle weight minimization. The structure not only acts as the supported component but also acts as actuator for control of the vehicle direction. From the control architecture diagram, described in figure 3-16, one can see that the directional control is achieved by tilting the rotation plane of both rotors toward the desired direction of motion through the deformation of flexible frame. This deformation changes the collective of the rotors in a cyclic manner such that the collective pitch is at a minimum for advancing blade and maximum for retreating blade, hence, caused the rotors to change their rotational plane to desired direction.

Research at Osaka Prefecture University, Japan

Two micro coaxial rotor models in dual motors configuration had been designed and constructed at Osaka Prefecture University (OPU), Japan with the research goal of using this kind of MAV as a tool to assist everyday life [26].

The first model, shown in figure 3-16, is a pure dual motor coaxial helicopter. Each of upper and lower rotors of this battery-powered helicopter has two blades with diameter of 35cm. The upper rotor is equipped with stabilizer bar to obtain passive control in pitch. The lower rotor is connected to two servo motors for controlling the longitudinal and lateral cyclic pitch. A duct that surrounds either the lower rotor or both rotors was added to increase stability and safety.

Avionics system, included rate gyro; declinometer; receiver and microcomputer, combined with IR range finder and IR photodetector gives the vehicle the ability of autonomous flight as well as following a robot or person that has IR light. Micro camera with wireless connection to ground station is also used to widen the visual range of the pilot.

Figure 3-16 Coaxial helicopter with duct

This coaxial helicopter later was modified with the adding of pitching tail propeller, permitted it to be used in both indoor and outdoor applications [27].

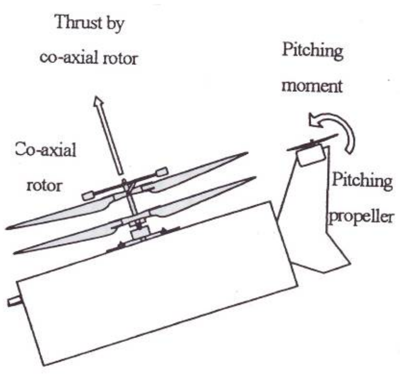

Figure 3-17 Coaxial with pitching tail propeller

This second flying robot developed at OPU, is slightly heavier than the first one with the weight of 400g including 50g micro camera and 50g flight controller.

The flight test in the late version in the year of 2006 showed that the vehicle could stabilize at the aimed altitude of 15m in wind condition of 1m/s and was able to take image from this altitude.

3.4.2.3 Multi-motors micro coaxial helicopter

As its name, multi-motors helicopter uses more than two motor for thrust generation and control. The mechanism and control of the vehicle are different depend on the number of motors used.

Research at Swiss Federal Institute of Technology Lausanne

Figure 3-18 describes a multi-motors coaxial rotor, name CoaX, designed and constructed at Autonomous System Laboratory (ASL) [28], Swiss Federal Institute of Technology Lausanne. Two main rotors are driven by same motor to generate thrust to counter the weight and the parasite drag acting on the fuselage; while three lateral rotors independently driven by three motors are used to achieve rotation and translation.

There are some innovations in this model. Flexible propeller and inertia ring is used instead of classical fly-bar system to achieve passive stability. There is no swashplate system and servo motor attached to the lower rotor for controlling direction.

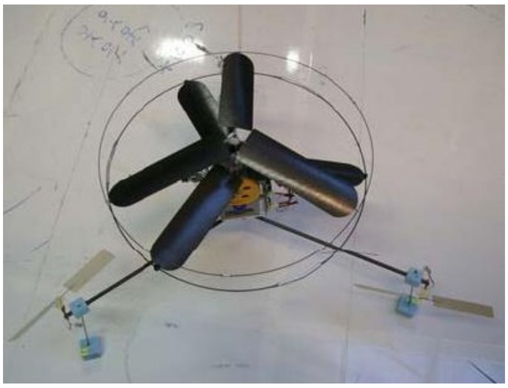

Figure 3-18 CoaX model developed at ASL

Both upper and lower rotors are only being controlled in the rotational speed, which permits to control the altitude of the vehicle. These concept leads to the mechanical simplicity and weight reduction in control system. In order to control the rotation and translation of the vehicle, three small lateral propellers, placed at

120^0 in the horizontal plane are used. The principle to achieve desired rotation or translation motion is represented in figure 3-19.

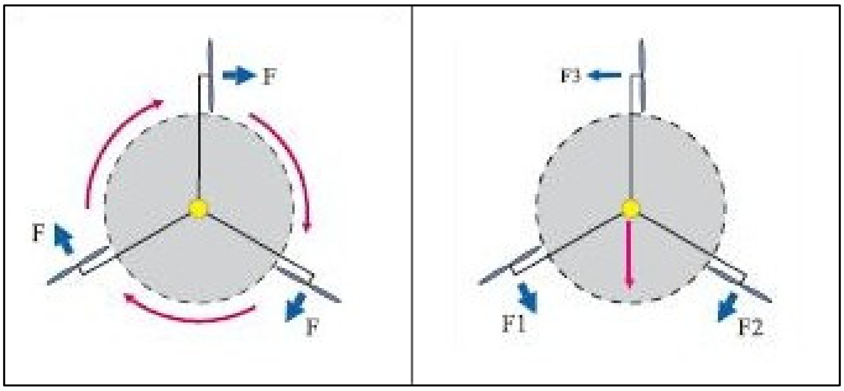

Figure 3-19 Control of rotation and translation

By using lateral propellers, the vehicle can translate in both directions and rotate at the same time. This control solution is simple, but it decreases the robustness, survivability as well as increases the system volume and power consumption.

To overcome these drawbacks, the idea of shifting the center of gravity by controlling the battery's position is used instead of swashplate system or lateral propeller [28]. This replacement makes the model much more compact and easy to achieve translation. One can observe in figure 3-20 that the CG shifting system only uses two servo motor and two semi-circular guides while the battery is attached to the vehicle body through a kneecap mechanism. These two servos can be controlled separately or simultaneously to move the battery in one axis or two axis, resulting in one or omni-direction motion.

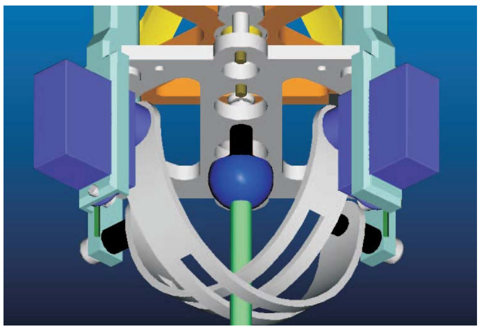

Figure 3-20 CoaX and its CG shifting system

3.4.2.4 Research on modeling and control of coaxial rotor

Modeling of micro coaxial as well as developing autonomous control system for indoor coaxial helicopter also attracted a significant contribution of researchers in the field.

At School of Computer Science and Software Engineering, University of Wollongong, LiChen devoted on modeling the dynamics of Hirobo's micro coaxial helicopter, namely Lama X.R.B. This research covered the basic characteristics and the modeling processes of the most common platform of coaxial helicopter. Comparison between coaxial rotor and quadrotors was also represented to show the difference in dynamics and how they impact in control [7].

A more general research on dynamic modeling and control of coaxial helicopter had been carried out at Center de Recherches de Royallieu, England by Pedro Castillo, Rogelio and T.Hamel. This study gives a general trajectory for mathematic modeling of coaxial rotors as well as introduces an optional solution for control using classical control method [29]. Firstly, dynamics model of coaxial helicopter is derived from the Newton's equation of motion, consisted of translational forces and rotational torques applied to the helicopter. Then, full trajectory of the vehicle can be obtained by solving these dynamic equations with one of control methods. The available control method consists of Lyapunov theory, PID control technique; optimal control theory, backstepping technique and side mode technique [30].

3.5 Concluding Remarks

Advantages and drawbacks as well as brief history of coaxial helicopter have been discussed in this chapter. Coaxial helicopter has the advantage to counteract torque without the used of tail rotor, and to solve the problem of asymmetric lift. The main drawbacks are rotors interference and control system complexity. The history of coaxial helicopter was remarked with main events in solving the technical problem during its development.

This chapter also discusses how the micro coaxial is simpler than the large one in terms of mechanism and control. Then, the introduction of some recent and current researches in several universities and research centers helps to make the classification of micro coaxial helicopter become more clear in the aspect of system composition as well as control architecture.