Articles

The Intricacies of Rotorcraft Design

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Introduction

In the autumn of 1986 a helicopter sped across the Somerset Levels achieving a world speed record for its class. This was the culmination of years of research, development and practical application and which resulted in a revolutionary rotor blade design. This enabled a Westland Lynx to overcome the aerodynamic limitations which plague the helicopter main rotor. To emphasise this, the speed achieved was 216 knots which was 63 years after a fixed wing aircraft achieved the same speed. So what is the problem – why should the helicopter have such a problem in achieving high speed flight?

Figure 1: Westland Lynx (Agusta Westland)

Over the years following the Wright Brothers' flight from Kill Devils Hill and Samuel Franklin Cody's achievements 100 years ago at Farnborough, a dream of aeronautical engineers has been the ability to take-off and land vertically and to be able to fly at a considerable speed. The former is possible in several ways from rotor to propeller to fan and then to jet thrust. However, because of its vertical take-off and landing capabilities, the helicopter is a different type of aircraft and in order to compete with a conventional aircraft it needs to be able to hover and, in addition, to convert into and out of forward flight. These place different requirements on the aircraft design and to be able to attain both together generate unique challenges for the helicopter designer. It must be able to operate in these flight regimes economically which is particularly appropriate in the world today where lowering fuel consumption requires the designers to constantly monitor the power requirements.

Efficiency in the hover can be examined using relatively simple theories which show that a large diameter rotor is the most efficient solution. As helicopters spend a proportion of their flight time at low speed, or in the hover, conventional designs tend to have a large diameter rotor. The power required in the hover is considerable and of the various contributions, the majority is required by the generation of the thrust force. This, so called, induced power forms about 70% of the total required to hover.

As well as attaining an efficient hover, the helicopter must now be analysed as it moves into forward flight. The power components change considerably as the rotor(s) experience the effects of forward flight speed. The induced power, which dominates in the hover, reduces significantly as the forward speed provides a ram effect. Conversely, the power consumption required to overcome the parasitic fuselage drag force, which is equal to zero in the hover, now becomes the dominating factor at higher speeds. The power necessary to overcome the aerodynamic drag of the rotor blades themselves (profile power) increases more modestly. The rate of increase of the profile power, with forward speed, remains modest providing the blades do not experience stall. However, this increase will be much greater if the rotor penetrates the stall boundary. An examination of the power component variation with forward speed shows that a significant dip in the total power occurs at a speed of around 70 knots after which it increases to a value similar to the hover at its maximum speed. This characteristic power variation significantly influences the manner in which the helicopter is flown.

It has been a continuing aspiration to design a helicopter to fly at higher forward speeds. Unfortunately, in addition to overcoming any power limitations, the rotor(s) themselves suffer from aerodynamic limits which have prevented the conventional helicopter from achieving high speed forward flight. The ability to hover efficiently and to fly at high forward speed is not economically achievable. The search for the combination of vertical take off and high forward speed in a single air vehicle has a long history. A large rotor diameter, as used in the helicopter is not entirely appropriate for forward flight as a propeller. The idealised blade geometry differs significantly between them. For this reason there have been many different rotorcraft configurations devised, built and flown. These will be discussed later, but first the aerodynamic difficulties of a helicopter rotor need to be examined.

The Rotor Problem

The rotor is mounted on the fuselage with the shaft essentially vertical. This is ideal for the helicopter in hover to support the weight, but as the aircraft commences forward flight, the rotor moves in an essentially edgewise sense. This is fundamentally different to a conventional propeller which moves along its axis of symmetry. In addition, the main rotor is the only means, in a conventional helicopter configuration, of providing the forward force component to overcome the drag and hence sustain forward flight.

There may be circumstances in which a large main rotor size may not be feasible. In such circumstances the helicopter will not be able to hover with same efficiency. This is appropriate for later versions of rotary wing aircraft where they can convert from helicopter mode to fixed-wing mode such as the BA609 tilt rotor aircraft. Therein lays the conflict. The layout of the main rotor, or main rotors, and possible tail rotor gives rise to the many different types of rotorcraft configurations that are seen today and of the future.

The advancing side is where the rotor blade is moving in the same direction as the helicopter – relative to the air. The retreating side is where they are moving in opposite directions.

This edgewise motion of the main rotor combined with the forward speed produces a difference of aerodynamic conditions between both sides of the rotor. Because of the relative motion directions of the rotor blades and the fuselage, the rotor naturally divides into two halves, separated by the longitudinal diameter. These two divisions are termed the advancing or retreating sides. (The advancing side is where the rotor blade is moving in the same direction as the helicopter – relative to the air. The retreating side is where they are moving in opposite directions.)
This applies to the original rotary wing vehicle – the autogyro – and one of the pioneers was the Spaniard, Juan de la Cierva. In his original career, he was familiar with the use of trusses to isolate mechanical components from transmitting moments between each other. This knowledge enabled him to devise the solution to the problem that if nothing else was changed on the main rotor the dissymmetry of lift would cause a roll moment to develop which would ultimately cause aircraft to roll over out of control. He used his experience and came up with the concept of

using hinges which enable the rotor blades to move in a vertical sense out of the plane of rotation, known as flapping. The inclusion of flapping hinges isolates the hub from the rotor blades – and inconsequence – the blades from the hub. This has two consequences; firstly the blade position in the flapwise sense is governed by the balance between the aerodynamic lift, increasing the flapping angle, and the centrifugal force, decreasing it. The difference in the flow velocity between the advancing and retreating sides of the rotor disc (the plane traced out by the blade tips), causes the rotor to flap up at the front and down at the rear. As the rotor thrust vector is normally considered to be perpendicular to the rotor disc, the rearward disc tilt will create a rearward component of thrust which will decelerate the aircraft. In fact, in order to avoid the rolling moment, the inclusion of flapping hinges, in isolation, will prevent the helicopter from achieving sustained forward motion. The tendency for the rotor disc to tilt rearwards has to be reversed which will then permit the thrust to have a forward component which will overcome the drag force and sustain the forward motion.

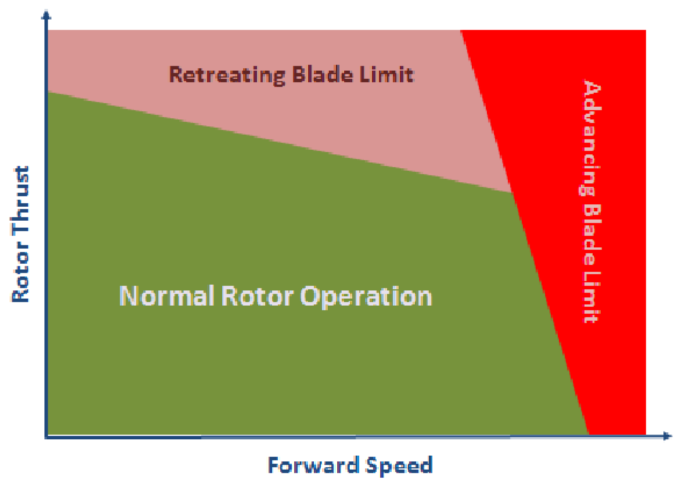

Figure 2: Rotor Limits

We therefore have the situation where as the helicopter attains forward flight, control of the rotor must be provided and the generation of forward propulsion requires that each rotor blade must be subjected to a once per revolution variation in pitch angle. This overcomes the effect of the velocity over the blades (advancing/retreating sides) and forces the blades to flap up at the rear of disc and down at the front. This blade pitch variation, at a frequency of once per revolution, is known as cyclic pitch. This brings in the second effect of the provision of flapping hinges which is a distinct disadvantage. As the forward flight speed increases so the thrust potential of the main rotor decreases. Maximum lift can be generated with a high dynamic pressure over the blades coupled with a high pitch angle. The situation of the advancing side and retreating sides of the rotor is directly opposite to that situation giving a thrust limitation with increasing forward flight speed. The retreating side tends to give the majority of the difficulties as the rotor blade speed through the air is reduced and extra pitch is required to balance the rotor in roll. Even though the advancing side has an increased speed of airflow over the blades, it tends to have a problem at the very highest forward speeds where the Mach number over the blade tip regions puts a severe limitation on the aerodynamic lift of the rotor and therefore it tends to appear as an abrupt limit to the forward flight speed. These limits are shown diagrammatically in Figure 2.

Aerodynamic design has improved the performance of a helicopter rotor enabling higher speeds to be obtained - as personified by the World Speed Record Lynx. However, to attain a flight speed comparable with fixed wing competitors, a complete change in the aircraft configuration and manner of flight is necessary, which has resulted in a wide range of aircraft designs.

Single Main and Tail Rotor Configuration

This particular configuration is the most common type and the main rotor provides control in five of the six axes, namely the three translations plus roll and pitch. To cater for the final degree of freedom of yaw, a rotor is placed on a boom at the tail end of the aircraft, rotating in a vertical plane. The thrust is varied by the pilots yaw controls (foot pedals) which gives a variation in torque about the main rotor shaft axis. This overcomes the torque reaction of the main rotor drive and also permits changes in aircraft yaw position.

This configuration is characterised by a large main rotor which makes it efficient in the hover and has a very extensive range of uses. As the main rotor provides the support for the aircraft, trimming in pitch is very sensitive to the mass distribution over the complete aircraft which results in a very small longitudinal centre of gravity range. A good example of this type of aircraft is the EH101 - Merlin which is shown in Figure 3.

Figure 3: EH101 Merlin (Agusta Westland)

Tandem Configuration

The tandem configuration has a main rotor placed at each end of the fuselage rotating in opposite directions. This enables yaw control to be achieved without the provision of a tail rotor. Since the aircraft is supported by the main rotors longitudinally placed at each end of the fuselage, the centre of gravity range in the longitudinal direction, for this configuration, is very large with longitudinal trim being achieved with differential rotor thrust. In forward flight the rear rotor has the potential problem of flying in the aerodynamic wake of the front rotor. To minimise this effect, the rear rotor is located at the top of a pylon which raises the disc plane above that of the front main rotor. This can be seen in Figure 4. For level flight this works very effectively, however, when the aircraft is coming into land, in order to decelerate, the rotor thrusts need to tilt rearwards and the fuselage adopts a nose up attitude. This pitch rotation causes the rear rotor to move downwards which positions it in line with the downwash from the front rotor. This change in relative position results in the rear rotor working in effectively a downdraught. There is now a danger of the rear of the aircraft sinking further. This is a particular problem when flying close to ground especially when coming into land.

Figure 4: CH46 (US Navy))

Placing the main rotor on the rear pylon raises the rear rotor disc plane above that of the front rotor. This creates the generation of forces and moments which couple the various degrees of freedom. For instance, if the helicopter executes a circular turn the front and rear rotors are tilted in opposite senses to create the yawing moment required to turn the fuselage in yaw. The rotor thrust forces are usually taken to be normal to the rotor discs which means they are inclined to the vertical in opposite directions. As the rear rotor is placed above the plane of the front rotor, these inclined thrust forces will form a couple both in yaw and roll and the aircraft will therefore tend to roll in addition to yaw. If the aircraft is flying forwards, then the rolling direction is in the opposite sense to what is normally considered a coordinated turn (i.e. rolling INTO the turn). An adverse coupling can also be generated if the centre of gravity is not placed at the mid point between the rotors. The position of the centre of gravity will make one rotor have a thrust in excess of the other rotor to maintain pitch trim. In the situation of the aircraft flying sideways the different thrust values, when tilted sideways will create a yaw coupling which will cause the aircraft to turn and a pure sideways motion is prevented. Whilst there are potential difficulties, the tandem configuration is an extremely valuable transport type of helicopter and a good example is the Boeing Vertol CH-46 shown in Figure 4.

Side By Side Configuration

In contrast to the tandem configuration, where the rotors are placed longitudinally, the two main rotors in the side-by-side configuration are located laterally on either side of the fuselage. As in the tandem, the rotors rotate in opposite senses giving the required yaw control. In forward flight, both rotors experience the same incoming airflow and therefore the problems of rotor interference seen with a tandem helicopter do not apply to the side by side configuration. The centre of gravity range with the side by side configuration is in a lateral sense. As the fuselage is in a longitudinal sense, this at first sight seems somewhat superfluous.

Figure 5: Mil 12 (Erik Frikke)

However it does afford such an aircraft the ability to fire weapons, which would normally be positioned laterally along the structure supporting the rotors, and roll trim can be maintained by adjusting the main rotor thrusts. The positioning of the main rotors also allows the fuselage extremities -the nose and tail sections - to protrude from outside of the periphery of the rotor disc planes. With the nose section of the fuselage protruding forward of the main rotor discs there is now the potential for crew ejection, in a vertical direction, whilst avoiding the rotors. Also with the tail section protruding rearwards from the two main rotor discs allows a weapon sight to be fitted to a gantry which can extend upwards and remain clear of the rotors. Hence, an observation platform can be placed above the plane of the rotors without the need for communication paths to be located within the rotor shaft which is what is normally seen with the single main rotor configurations. A good example of this configuration is the Mil 12 as shown in Figure 5. The layout of the rotors requires an extensive supporting structure. This, of course, will add a significant amount to the drag of the aircraft.

Coaxial Configuration

With the rotors placed at extreme positions the tandem and side by side configurations occupy a considerable volume. This is does not present an immediate difficulty when considering land based operations (operations close to trees excepted), however, with shipborne operation storage volume is at a premium. The coaxial configuration has both rotors placed on the same axis of rotation, rotating in opposite directions.

Figure 6: Kamov Ka32 (Luis Rosa)

Roll and pitch control is achieved by tilting both rotor together whilst yaw control is achieved by differential torques on the rotors. With one rotor being placed below the other, the downwash from the upper rotor must pass through the lower rotor. This will have ramifications for hover performance - as a rule of thumb, coaxial helicopter performance in the hover is often considered to be equivalent to that of a single main rotor helicopter supplying the total thrust required with the coaxial rotor radius.

operations close to trees excepted

This will increase the hover power as the rotors are usually smaller in diameter. As the coaxial configuration operates very much as a single rotor helicopter, the centre of gravity range is also very limited. With the two rotors rotating in opposite senses there is no need for a tail rotor to provide yaw control. This gives a very compact configuration which makes it suitable for shipborne operation. This is well shown with the Kamov type of aircraft, an example which is shown in Figure 6.

Synchropter

The coaxial helicopter has rotors placed on the same rotational axis. However, two rotors can be incorporated on separate shafts by correct inclination of them relative to the fuselage. Each rotor has its own shaft which is inclined outwards and, by correct rotational phasing of the rotors, any clashing between the two rotors is avoided. The synchropter variant was founded by the pioneer Anton Flettner and is normally associated with the Kaman helicopter company. Their Huskie and K_{MAX} aircraft are good examples of these consisting of two rotors with two blades. The controls for each rotor can be separate as there are now two rotor shafts, unlike the coaxial configuration however, the advantage of a compact layout and yaw control are still retained. This compactness makes it particularly suitable for use in confined areas such as logging and ship to ship transfer. This has given the

K$_{\text{MAX}}$ a niche market and is often advertised as an aerial truck and an example is shown in Figure 7. Kaman aircraft have a particular type of control system.

Figure 7: Kaman K$_{MAX}$ (Stewart Penney)

Most manufacturers achieve rotor control using a system operating on the rotor blades themselves by altering the blade pitch at the root end by mechanical linkages. With the Kaman type of aircraft, the blade pitch change is achieved through the elastic twisting of the rotor blade achieved by the aerodynamic pitching moment generated by a trailing edge flap positioned approximately two-thirds of the way down the rotor blade itself. This can be seen in Figure 7.

Convertible Rotor

To obtain higher flight speeds but still be able to take off and land vertically, new configurations have been developed over the years in order to overcome the limitations caused by the rotor aerodynamics. One solution is achievable by rotating the rotor shafts in pitch by which means the supporting force in hover can be transferred to forward propulsion in conventional forward flight. As the aircraft attains fully developed forward flight, the rotors are aligned axially and the advancing/retreating blade problem is now avoided. This type of solution has spawned two particular variants, namely the Tilt-Rotor or the Tilt-Wing. Amongst present day aircraft designs, the tilt rotor is typified by the BA609 aircraft, which is shown in Figure 8.

Figure 8: Agusta Bell BA609

In the hover it operates in a similar mode to a side by side configuration helicopter; however, the two rotors are able to rotate with their nacelles about a horizontal axis and, after fully rotating, point forwards. The aircraft is now transformed into a twin propeller-driven fixed-wing aircraft. Because the rotors have to rotate about the horizontal axis, the rotor radius is limited in size to avoid interference with the fuselage. The reduced rotor size will raise the hovering power. Since the rotors now have to operate in the roles of a supporting rotor for VTOL (or helicopter mode) and a propeller in forward flight mode, the geometry of the rotor blades must now be a compromise. Conventional propeller blades are highly twisted so as to align the blade sections correctly with the forward motion which is in an axial sense. This is usually of the order of 60° to 90°. Conversely, a helicopter rotor blade usually has a twist in the region of 8° to 10°. A convertible rotor blade twist will lie somewhere between them, say 50°.

Compound Helicopter

As outlined in the introduction, an edgewise main rotor, which supplies both support and drive for the helicopter, forms one of the main limitations of helicopters which is the forward flight speed trap. As the problem is rooted in the main rotor having to supply the lift and propulsion, one way past the speed trap is to divorce the requirements of having to support the weight of the helicopter and to provide the forward propulsive force. This is the concept behind the compound helicopter configuration. It achieves this solution by providing a fuselage with wings to offload the rotor together with an auxiliary propulsion device. A particularly good example of this type of configuration is the Lockheed Cheyenne helicopter of the late 1960's and early 1970's, which is shown in Figure 9.

Figure 9: Lockheed Cheyenne (Lockheed)

This aircraft took the concept of a single main and tail rotor configuration to which was added stub wings and a pusher propeller at the rear of the tail boom synchronising with the tail rotor. With this layout both the vertical and horizontal force balance of the aircraft could be adjusted independently of each other using the main rotor and pusher propeller blade pitch respectively. This particular aircraft achieved great speed but, as with all winged rotorcraft, suffered in the hover. The stub wings are correctly aligned in forward flight but as the helicopter translates to the hover they now become effectively at 90ř incidence. The rotor downwash will now generate a large downforce on the fuselage structure which in consequence requires the helicopter rotor to generate a still higher thrust level. (*This is technically known as rotor blockage.*) All main rotors suffer from a degree of blockage with the fuselage interrupting the downwash but wings accentuate this effect.

The provision of stub wings made the Cheyenne an aerodynamically efficient weapons platform and the provision of the pusher propeller gave the pilot close longitudinal control of the aircraft. This was achieved by providing a driving force to the helicopter for the high-speed operation and to behave as an airbrake if the aircraft is in a dive.

A totally different type of aircraft developed as a compound is the Rotodyne - see Figure 10 - and was designed by Fairey Aircraft in the 1950s. The essential difference with this design is that it used a tip drive for the main rotor. Forward propulsion was provided by a pair of airscrews. The airscrews were installed directly on to engines placed in nacelles on short wings projecting from the fuselage. Pressurised air was taken from the engine and transferred via ducts in the rotor hub and blades. This was then turned through a right angle and ejected rearwards providing the power to drive the rotor. The air bleed was taken from the compressors of the Napier Eland gas turbine engines and fed through the system of valves and seals along the rotor blades to the tip jets. Each engine fed a pair of opposing rotor blades giving a balanced torque in case of an engine failure. An essential difficulty of this type of reaction rotor propulsion is that the tip of each blade is moving fast relative to the air. The jet efflux needs a high velocity in order to develop the necessary propulsive thrust by overcoming the rotational velocity of the blade tips. With the Rotodyne rotor design, the pressurised air was not sufficient and so the pressure air thrust was augmented by feeding fuel along the rotor blades to the tips and burning it essentially as an afterburner. This had the distinct disadvantage of creating a considerable amount of noise which proved a very difficult problem for the eventual marketing of the aircraft.

This regime allowed the aircraft to take off and land vertically and operate in flight close to the hover. In forward flight, the airscrews provide the propulsion whilst the pressurised air from the engines was progressively shut down. The main rotor was allowed to tilt rearwards and operate like an autogyro deriving rotor power from the upward flow component of forward speed caus-

ing the rotor to autorotate. The wings supplied a proportion of the lift in forward flight and a full empennage gave the Rotodyne its weathercock stability. Differential airscrew thrust was used to give yaw control in and around the hover.
Technically it still achieved forward flight speeds which are still impressive for rotorcraft of today.

Figure 10: Fairey Rotodyne (Agusta Westland)

Final Remarks

This paper has provided a brief survey of the various types of rotorcraft which have appeared in the past 70 years. The range can be seen to be many and varied.
The helicopter supplies a niche and will therefore appear in a variety of guises, each designed to a particular requirement and to fulfil a particular purpose.
The ability to take off and land vertically under full control, coupled with an ability to transfer to and from substantial forward flight speed is a considerable proposition.
VTOL has unique benefits but it has to pay a considerable price. The continuing search for high speed has fuelled the many number of research projects seen over the years.
Amongst the many decisions that need to be addressed are:

How to drive the rotor system?
In the majority of rotorcraft designs; this uses internal engines which, in order to possess the required yaw control, a tail rotor device or a multi-main rotor layout is used. The transmission system provides mechanical support for the aircraft and so operates under considerable flight loads in addition to accepting the engine torque, modifying the rotational speeds and splitting the drive between the various rotors. It is a vital component and much effort is devoted to its design and installation in the airframe.

The rotors can also be driven externally via tip propulsion. With this regime no additional controlling torque is necessary for the yaw control of the aircraft fuselage. In addition, this now removes the need for the extra tail rotor transmission. This type of propulsion has been developed in the past and, with recent aircraft projects, is being examined for the future - this type of rotorcraft still has its potential. Since the propulsive drive is via jets with small diameters, the efficiency will not be as high as a conventional rotor system with the attendant higher usage of fuel. The question is how to spend your money; the choice is either an internal drive system which is more efficient but carries the weight penalty of a transmission or a tip drive propulsion system which less efficient but the reduced weight has the ability to carry the extra fuel required. Introduce the potentially higher flight speed and the decision becomes particularly profound.
The arrangement of the rotors is the final decision. There is no immediate answer as the operational requirements of the design have a total influence on the airframe configuration. The many different layouts of the rotors illustrate the many different operations the rotorcraft has been asked to fulfil.

As a final comment, the question can be asked as to whether a helicopter configuration could replace a transcontinental type of fixed wing aircraft. It would benefit from the VTOL capability, but the speed and range would be, almost certainly, inferior. CTOL is still the choice since it has the long range capability.
Rotorcraft cannot solve all of the many problems, however, their efficiency in and around the hover, together with the effectiveness afforded by the VTOL capability will ensure that they will always have a contribution to make in the future of aeronautics.