Performances Comparisons of Different Rotary Wing UAV Configurations

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Nomenclature

b	number of blades,
c	blade chord, (m)
C_x, C_z	drag and lift coefficients,
DL	rotor / wing download, (N)
D_{nac}	nacelle tilt angle, (deg)
F_n	thrust of one rotor, (N)
F_t	total thrust of all rotors, (N)
μ	advance ratio : $V_h/(\Omega.R)$,
R	rotor radius, (m)
S	rotor disk surface, (m^2)
S_c	contracted blown surface in hover, (m^2)
S'	blown surface in forward flight, (m^2)
V_{be}	speed of best endurance, (km/h)
V_{br}	speed of best range, (km/h)
V_h	rotorcraft horizontal speed, (km/h)
V_i	rotor induced velocity, (m/s)
Vi_1	induced velocity through the upper rotor, (m/s)
Vi_2	induced velocity through the lower rotor, (m/s)
ρ	air density, (kg/m^3)
σ_e	equivalent rotor solidity
Ω	rotor rotational speed, (rad/s)
HIGE	Hover In Ground Effect
HOGE	Hover Out of Ground Effect
ISA/SL	International Standard Atmosphere / Sea Level
-RS	relative to the upper rotor
-RI	relative to the lower rotor
RWUAV	Rotary Wing UAV
UAV	Uninhabited Aerial Vehicle

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Abstract

This paper presents the basis of models and tools built by ONERA for assessing the performances of different RW-UAV configurations, mainly : the single main rotor helicopter, the coaxial rotorcraft and the tilt-rotor. These simulation tools have been created or adapted to this purpose during the European project CAPECON. A significant work has been done by ONERA for modelling the aerodynamic interferences, especially for the coaxial rotors. The first level of these tools is the analytical assessment of the required power by the energy method. The second level is the non-linear comprehensive flight mechanics simulation of these rotorcrafts. The third level is the iterative computation of the required power and the fuel consumption during an entire mission including hover, climb, cruse, …

Introduction

Rotary Wing Uninhabited Aerial Vehicles (RW-UAV) have a high potential of civil and military applications, thanks to their Vertical Take-Off and Landing (VTOL), hover and low speed capabilities. They have attracted the interest of a lot of studies around the world. One recent example is the European project CAPECON (*Civil UAV APplications & Economic Effectivity of Potential CONfiguration Solutions),* in which three groups have worked in parallel. Two groups have investigated fixed wing UAVs : one the High Altitude Long Endurance concept (HALE-UAV) and the other the Medium Altitude Long Endurance (MALE-UAV). The third group has been dedicated to RW-UAV. A synthesis of the work carried on in CAPECON on RW-UAV is exposed in another paper [1] : from the survey of potential civil applications until investigations for preparing the design of the entire system (air vehicle, onboard equipments and ground control station). Yet tilt-rotor UAVs have not been considered in CAPECON and reference [1] is focused on the coaxial configuration (two contra-rotating rotors one above the other).

This paper addresses the key problem of comparing the performances of different RW-UAV configurations, mainly : the single main rotor / tail rotor helicopter, the coaxial rotorcraft and the tilt-rotor. Although dealing both with RW-UAV, the scope and purposes of the two papers are therefore completely different. Indeed, the present paper is devoted to the comparisons of the air vehicle performances, whereas that topic is not considered in [1].

The coaxial configuration with two contra-rotating two bladed rotors (CAPECON configuration) will be compared with an equivalent four bladed single main rotor helicopter. The comparisons will then be extended to an equivalent tilt-rotor UAV (adapted from the Eagle Eye UAV). Specific mathematical models for each kind of these rotorcraft UAVs will be described. ONERA has been contributing for years to the model developments for the simulation of helicopter and tilt-rotor flight dynamics, for which some examples have been presented in previous papers [e.g. 2-4 and 5-7]. That is why more emphasis will be given here to the description of the coaxial model and more precisely about the modelling of the aerodynamic interferences between the two coaxial rotors.

Three levels of simulation tools for assessing the performances will be presented. The first one is based on the classical energy method which makes use of analytical expressions for a first power estimation. The second level uses a comprehensive rotorcraft flight mechanics simulation code that ONERA has adapted for the coaxial configuration during the CAPECON project. For a third level of practical comparisons, the flight mechanics simulation model has been implemented in a more general program for computing the performances on the different parts of a complete mission profile. The performances of the different RW-UAV configurations can then be compared on a typical mission including : hover, climb, cruse, descent, loitering flight, …

The aerodynamic interference model for coaxial rotors will be first presented and then the three kinds of tools for performances comparisons.

INFLOW MODEL FOR COAXIAL ROTORS

The most important difficulty in the modeling of a coaxial configuration for performance estimation as well as for flight dynamics simulation, concerns the aerodynamic interferences between the rotors. This question is crucial because the rotor induced velocities are strong and a realistic model can not ignore them.

Background

The simplest approaches for estimating the coaxial rotorcraft performances make use of single main rotor models. For example, the pre-design of the CAPECON coaxial configuration has been done by Eurocopter (see [1]) by adapting their well-experienced helicopter sizing tool based on the adjustments indicated in [8], mainly a reduction of the mean lift coefficient and the increase of the main rotor diameter for equivalent performances. The often used equivalent solidity single rotor approach with roughly 5% less required power, is also a good first approximation of the hovering performance of coaxial rotors [9]. However, for a more precise calculation, an increased level of modelling realism, as proposed in this part, is required in particular in forward flights.

Western Europe has of course less experience than the Kamov company, but this complex aerodynamic interaction between coaxial rotors was already addressed, e.g. by ONERA in 1949 [10]. The axial and rotational induced flow components were derived in [10] from potentials which were calculated on the assumption of helicoid vortex wakes. A more sophisticated approach is the free wake method presented in [11] with two free rotor wakes in mutual interferences.

The purpose of the model is here to be applied for performance assessment and flight mechanics computation. That is why ONERA has developed an analytical model closer to the physics than the equivalent single main rotor approaches and less time consuming than the vortex methods.

Hereafter the physics will be described and then the main lines of our proposed model.

The physics

In the case of coaxial rotors, the rotors are submitted to the following main phenomena. The upper rotor (rotor 1) blows down on a contracted surface on the lower rotor (rotor 2, see Fig. 1). The lower rotor (2) breathes down the air through the upper rotor (1). Therefore through both rotors, there is a part of downwash due to the other rotor. Moreover, the swirl effect makes that the upper rotor induces on the lower rotor a rotational induced flow in the opposite blade rotation direction of rotor 2. This effect increases the airspeed seen by the blades of rotor 2 (as if its rotation speed was higher) since the rotors are contra-rotating.

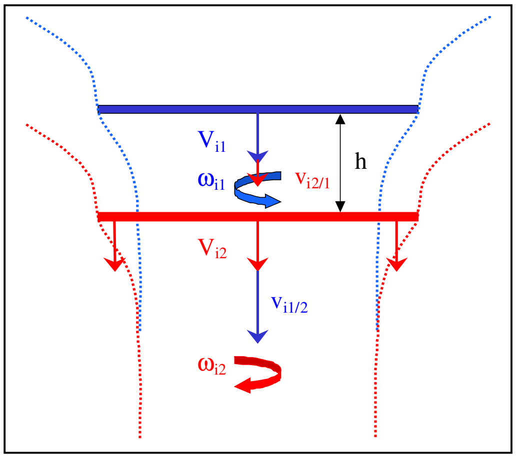

Figure 1 : induced velocities in hover or vertical flights for coaxial rotors.

In forward flights, the rotor wakes are swept backwards. Depending on the wake skew angle (χ) and thus on the forward speed, the blown surface by rotor 1 on rotor 2 decreases as shown by the smoke flow visualization on Fig. 2 extracted from [12]. This effect reduces the interferences.

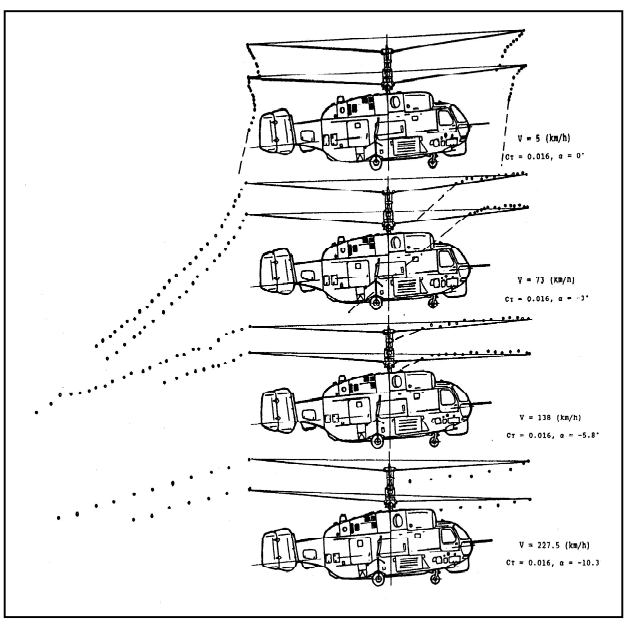

Figure 2 : the rotors wakes for different forward speeds in the case of the Kamov 32 [12].

The inflow calculation model

The model has been first focused on the axial induced velocities because they are stronger than the rotational ones. Indeed the blade airfoils being designed to develop more lift than drag, the induced downwash is also stronger than the swirl effect. An analytical expression, developed by ONERA [7] for taking into account the swirl effect by a tilt-rotor on the wing, shows that if the downwash is about 10 to 15 m/s the ortho-radial induced component remains close to 2 m/s.

This effect should increase the aerodynamic efficiency of the lower rotor, but seems to be negligible since the blade rotation speed near the tip is around 200 m/s. Therefore the calculation of the axial induced flow was the first priority. Yet for certain case of flights or maneuvers at low speeds with a high collective involving a high torque, it will demand to refine the model by accounting for the rotational induced flow.

Hover and axial flights :

In a first step, the two extra interference downwashs $\left(v_{i1/2}, v_{i2/1}\right)$ are determined by solving a system of two equations in which they are considered as additional inflows with respect to the mean inflow in the isolated rotor case $\left(V_{i1}, V_{i2}\right)$. These two equations are based on the mass flow rate conservation and on the momentum conservation.

The vertical separation (h) between the rotors is taken into account in the calculation of the contracted surface (Sc) blown by the rotor 1 on the rotor 2. For that we used ONERA wind tunnel test data giving the radial contraction of the rotor wake in function of the vertical distance below the rotor.

In a second step, the effective induced flow through each rotor $\left(V_{i1e}, V_{i2e}\right)$ are calculated by using the interferences $\left(v_{i1/2}, v_{i2/1}\right)$ as upstream conditions (as if each rotor was in climb or in a wind tunnel).

In forward flights :

Then the model has been extended to the case of forward flights by accounting for the fact that the rotors wakes are skewed backwards which reduces the surface of interaction (S') as illustrated on Fig. 3.

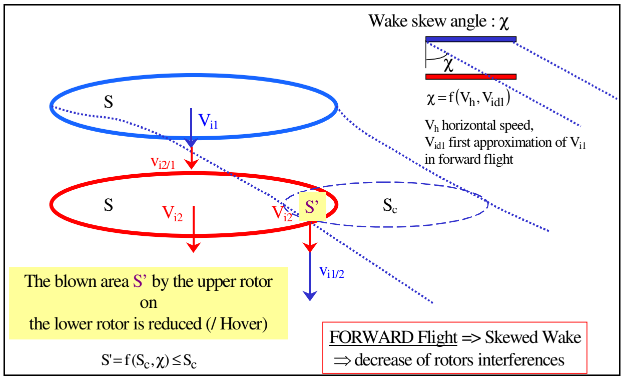

Figure 3 : Extension of the model to the case of forward flights.

The resolution of the extended system of two equations provides an estimation of the two axial interferences velocities $(v_{i1/2}, v_{i2/1})$ as sketched on Fig. 4.

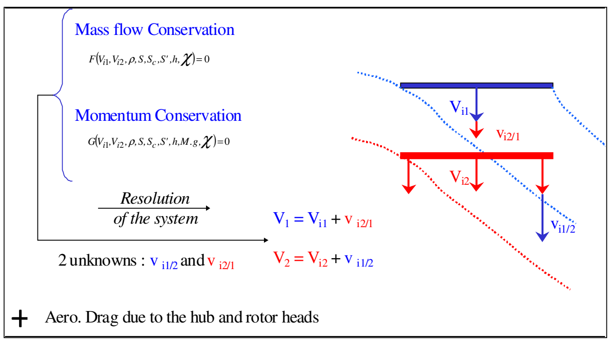

Figure 4 : calculation of the perturbation induced flow in forward flights.

They are then used as upstream conditions for calculating the effective own induced velocities through each rotor with the proposed formula :

$$Vi_{1e} = \frac{1}{2}\left[\frac{S'}{Sc}v_{i2/1} + \sqrt{\left(\frac{S'}{Sc}v_{i2/1}\right)^2 + 4.Vi^2_{1\_no\_int}}\right]$$

$$Vi_{2e} = \frac{1}{2}\left[\frac{S'}{S}v_{i1/2} + \sqrt{\left(\frac{S'}{S}v_{i1/2}\right)^2 + 4.Vi^2_{2\_no\_int}}\right]$$

Finally the total axial mean induced flow through each rotor is :

- for the upper rotor : $Vi_1 = Vi_{1e} + vi_{2/1}$
- for the lower rotor : $Vi_2 = Vi_{2e} + vi_{1/2}$

This model is comprehensive in the meaning that it represents in a continuous way three kind of regimes of the coaxial rotors :

- the case of hover and axial flight for which : S'=Sc
- the case of intermediate speeds for which : 0<S'<Sc
- the case of higher speeds for which : S'=0.

1ST LEVEL : ANALYTICAL COMPARISONS

Here the classical energy method is applied. The needed power (P_n) is calculated as being the sum of :

- the induced power : P_i
- the consumed power by the blade airfoils drag : P_p
- the fuselage drag power (all the sources of aerodynamic drag except those of the rotor blades airfoils) : P_f
- the anti-torque power in case of a configuration with a tail rotor : P_a.

On the other hand, the available power coming from the engine is estimated taking into account the power losses through transmission, etc. (estimated here to 5%). (P_u) is the effective usable power. This power depends of course on the considered flight point in terms of altitude and temperature. As will appear on the ceilings graph, we have taken into account a turbo-effect which makes that the power provided by the Centurion 1.7 engine decreases less with the altitude than a classical engine.

Coaxial power analytical estimation

For coaxial rotorcrafts, besides the rotors interferences, it must also be taken into account that the rotors mast will have more drag than a classical main rotor. For performance calculation, this effect is accounted for by increasing the global drag power (P_f) by around 20 %. This value was estimated by validating our calculation tool in the case of an existing coaxial rotorcraft : the Kamov 32 for which the main data and performances are known (e.g. in the "Jane's book" [13]).

Now let's consider the practical case of the coaxial CAPECON RW-UAV described in [1] and shown hereafter (Fig. 5).

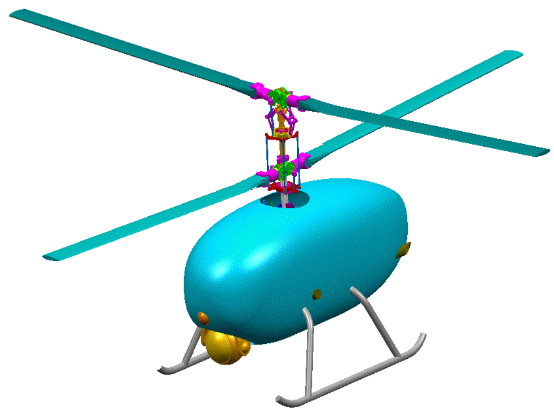

Figure 5 : CAPECON Coaxial configuration.

The input data in our performance calculation tool are based on the predesign and sizing presented in details in [1].

Input Data		
		Tip blade speed :
Take-Off Gross Weight (kg) :	499	
		U = 197,61 m/s
Number of blades for each rotor :	2	
Rotor rotational speed (rev/min)	740	
		Calculated Average Lift Coefficient :
Blade average chord (m) :	0,17	
		Czmoy = 0,4174
Take-off power ISA/SL (kw) :	100	
Tubine (T) or Piston (P) Engine :	p	
Distance between the rotors (m) :	0,51	
Rotor Diameter (m) :	5,1	*Calculated Global Lift Force :*
Front Fuselage surface Sx (m²) :	0,615	F_{nT} = 5091 N
Fuselage Drag coefficient Cd	1,05	

Figure 6 : CAPECON Coaxial data inputs.

In [1] ONERA has provided the results for the Max Take-Off Weight of 550kg. Here we present the results for the mass which was first considered in CAPECON : 499kg. That lets more margin with respect to the available power. First, for estimating the performances in forward flights, the different sources of power consumption have been calculated w.r.t. the forward speed with analytical expressions based on the energy method and the interferences model.

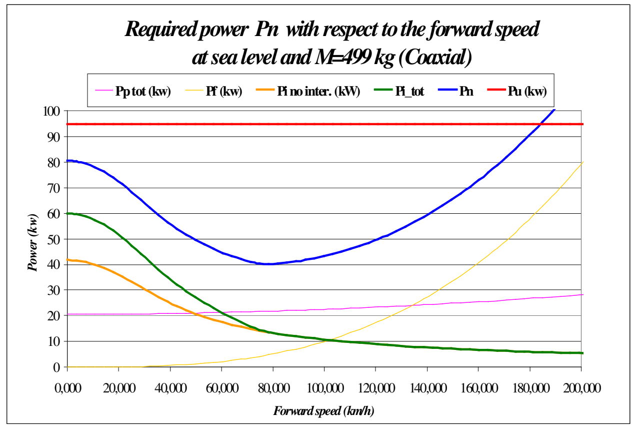

Figure 7 : Powers in forward flights for the coaxial.

On Figure 7, the induced power without rotor interferences has also been drawn ("Pi no inter."). It appears clearly that from hover until a forward speed around 75 km/h, the interferences increase the induced power. Indeed above ~75 km/h, the wake skew angle is such that the blown surface (S') is null and thus there is no more significant interaction.

The characteristic speeds : Vbe (best endurance), Vbr (best range) and Vmax (maximum speed), are assessed below (Fig. 8).

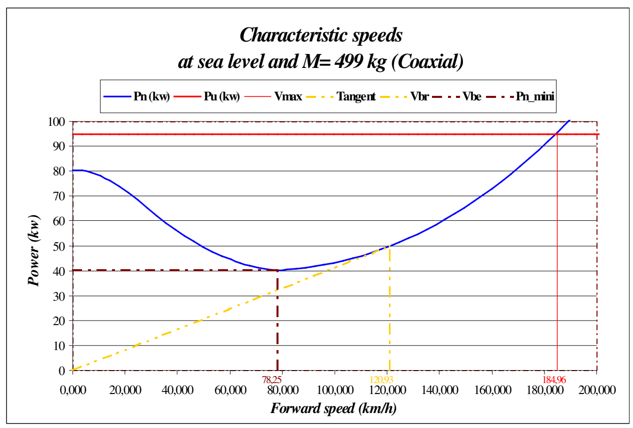

Figure 8 : Characteristic speeds assessment.

From this analytical assessment, the results at ISA/ sea level for M=449kg are :
Vmax ≈ 185 km/h, Vbr ≈ 121 km/h, Vbe ≈ 78 km/h

Comparisons with other rotor configurations

Detail comparisons have been performed with an equivalent helicopter having a single main rotor with four blades instead of two rotors with two blades and exactly the same design data as the coaxial, except that a tail rotor and a horizontal stabilizer are added.

Compared with the coaxial, the tail rotor is an extra source of power consumption (PaTR) for insuring the anti-torque function. But the power due to the overall drag (fuselage, rotor hub, etc.) is lower with the helicopter because of the big rotor mast in the coaxial case.

The comparisons of the powers between the coaxial and the helicopter are shown on Fig. 9. The results show that the required power is not only lower in hover and low speeds with the coaxial, but also at intermediate speeds. In hover, the coaxial requires less power because it avoids the tail rotor consumption needed by the helicopter (the difference is about 5~6%). At intermediate speeds (30~90 km/h), the difference is even more significant : the calculation indicates that the coaxial requires less power than the helicopter (about 26% less around 75km/h). That comes from the fact that the induced power decreases with the forward speed more rapidly in the case of the coaxial (see green curves). Then at higher speeds (crossing at about 170 km/h), the additional drag due to the bigger mast of the coaxial, leads to less maximum speed compared with the equivalent helicopter (Vmax≈188,5 km/h).

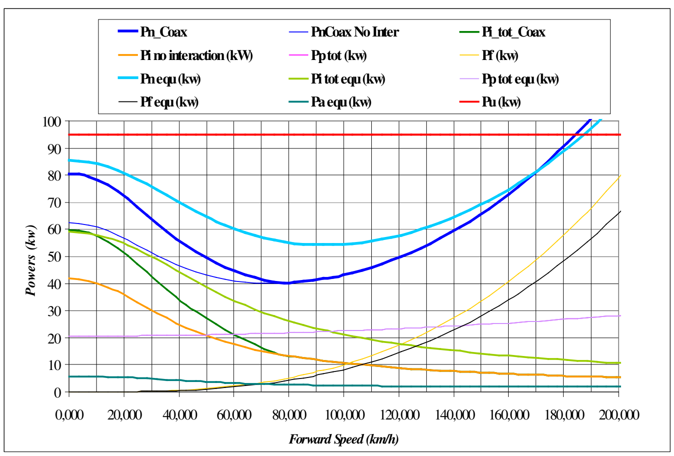

Figure 9 : Comparisons of the power needed by the coaxial w.r.t. the equivalent helicopter (M=499kg).

These modeling features lead to the result that the required power is lower with the coaxial from hover up to 140 km/h (more than 5% lower) and mainly at intermediate speeds.

Several consequences may be drawn with respect to the classical helicopter configuration. With the coaxial : the MTOW will be higher or for the same gross weight the ceiling will be higher, the endurance will be higher (at least for speeds up to 140~150km/h).

Noticing (Fig. 9) that without the aerodynamic interferences between the rotors, the induced power could be even lower, the comparisons have been extended to the case of two other configurations for which the rotors are not directly in interaction : the tandem twin-rotor and the tilt-rotor.

Since these concepts have not been retained in the studied RW UAV configurations within the CAPECON RW group, only the main principles of their performances calculation will be mentioned here.

For the **case of the tandem twin-rotor**, the two rotors exactly identical to those of the coaxial are located one above the front part of the fuselage and one above the bottom part without overlapping. The rotors are considered in the ideal case of no mutual interferences. The fuselage is longer than the one of the reference one. Moreover, this configuration has two rotor hubs. Therefore the fuselage drag is increased by 30% w.r.t. the equivalent helicopter one. Due to the induced download by the rotor downwash on a bigger fuselage, the considered weight is (1.07 × m.g) instead of (1.04 × m.g) in the helicopter case.

For the **case of the tilt-rotor**, a smaller rotor radius must of course be considered (R<2.55m), for example for avoiding the contact of the blades with the ground in the airplane mode. We chose to size the tilt-rotors such that they have an equivalent rotor solidity compared with the other configurations. As usual the rotor solidity is defined by :

$$\sigma = \frac{b.c.R}{\pi.R^2} = \frac{b.c}{\pi.R}$$

The coaxial and the equivalent helicopter and tandem configurations have the same total number of blades (b=4) with the same average chord (c=0.17m) and the same radius (R=2.55m) leading to the same solidity :

$$\sigma = 0.0849$$

For the equivalent tilt-rotor, it is more realistic to consider two three-bladed rotors (b'=3). The rotor speed is chosen such that the blade tip speed is the same (197.6m/s). The size of the Eagle-Eye (existing tilt-rotor UAV) is comparable with our configurations. Therefore we chose to use its rotor radius (R=1.25m). The blade mean chord is then :

$$c = \frac{0.0849.\pi.R}{3} \approx 0.11m$$

Writing that the rotor disc loadings are equal with the same tip speed and same average blade lift coefficient, that leads to a relationship between the aspect ratios giving the same results :

$$\left(\frac{R}{c}\right)_{tilt-rotor} = \frac{(b'=3)}{(b=4)} \times \left(\frac{R}{c}\right)_{helico}$$

The download (-DL) due to the rotor / wing interferences are taken into account by the following formula from [14] :

$$Fn - DL = Fn.\left(1 - \frac{0{,}1 . \sin D_{nac}}{\frac{\mu}{0{,}025} + 1}\right)$$

Where (Fn) is the thrust of one rotor. In hover, the nacelle tilt-angle is (Dnac=90°) and (μ=0), therefore : Fn = M.g/1.8

In hover, the model is close to the one used for helicopter performances assessment except this download effect and the absence of tail rotor power. The tilt-rotors are compact high loaded rotors with large chords close to the blade root and they are highly twisted. Therefore the induced efficiency has been considered higher than the other configurations :

$P_i = 1.05 \times P_{iTheo}$ (instead of : $P_i = 1.15 \times P_{iTheo}$)

In airplane mode, the power provided by the engines is mainly spent for making translate the aircraft at a certain speed. The wings provide the lift to counter the gross weight. The thrusts developed by the rotors overcome all the kinds of aerodynamic drag coming from : the fuselage, the wings, the nacelles ... Thus for calculating the induced power (P_i) by both rotors, we use the same expression as for a helicopter in vertical climb with the forward speed (V_h) replacing the climb rate (V_z) and the total drag force (F_{tx}) replacing the weight. Finally the required power in forward flight in airplane mode is the sum of the induced power and the rotor blade airfoils drag power.

The most important difficulty is then to build a model for the conversion mode insuring the smooth transition between the two main modes (helicopter and airplane).

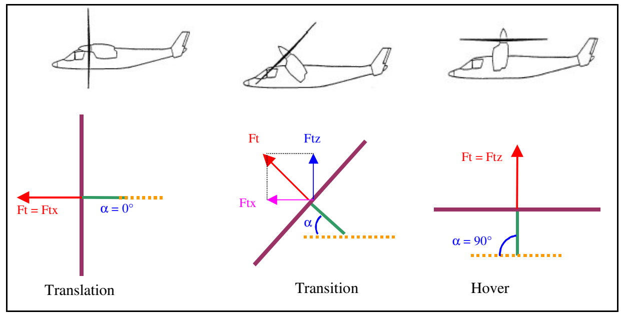

Figure 10 : Tilt-rotor airplane, conversion and helicopter modes.

For the transition, both the wings and the rotors contribute to balance the weight. Therefore, first we compute the (Ftz) component of the rotors thrusts taking into account the wings lifts and the downloads depending on the speed and on the nacelle angles.

$$Ftz = \frac{M.g}{1 - \frac{0{,}1.\sin D_{nac}}{\frac{\mu}{0{,}025}+1}} - \frac{1}{2}.\rho.V_h^2.S.Cz_w$$

Different kinds of tilt laws of the nacelles angles with respect to the forward speed have been modeled (linear, quadratic, elliptic). Here the transition from the helicopter mode to the airplane mode is done by tilting the nacelles with an elliptical law (Dnac in deg) :

$$\left(\frac{V_h}{V_{\min}}\right)^2 + \left(\frac{D_{nac}}{90}\right)^2 = 1 \Rightarrow D_{nac} = 90.\sqrt{1 - \left(\frac{V_h}{V_{\min}}\right)^2}$$

(Vmin) is the minimum speed from which all the lift is given by the wings :

$$V_{\min} = \sqrt{\frac{2.M.g}{\rho.S.Cz_{w\max}}}$$

Second, the (Ftx) component to overcome the total drag is computed as in the translation mode.

$$Ftx = \frac{1}{2}.\rho.V_h^2.\left(2.S_{nac}.Cx_{nac} + S_{2W}.Cx_w + 0.7.M^{2/3}\right)$$

$\left(0.7.M^{2/3}\right)$, with M the mass in tons, is a classical approximation for the drag of the fuselage giving a lower drag than $\left(S_F.Cx_F\right)$, since the fuselage of the tilt-rotor can be supposed with less drag.

Then the total thrust (Ft) can be calculated and hence the induced power. Finally the required power is estimated by assuming that the rotor airfoil drag power P_p is the same as in hover.

The comparisons of the required powers w.r.t. the forward speed are shown on Fig. 11. In hover and low speeds, the lower required power is obtained in the ideal case of a tandem rotorcraft without rotor interferences and the higher required power in the case of the tilt-rotor due to the higher induced power. Indeed the rotor radius of the tilt-rotor being smaller, the induced power is stronger as can be seen on Fig. 12. At higher forward speeds, the tendencies on the required power (Fig. 11) are inverted due to the higher fuselage drags on the tandem and coaxial. That results in a higher maximum speed for the tilt-rotor (Vmax≈216 km/h for Pu=95kW) even if the induced power of the tilt-rotor increases with the forward speed after the transition to the airplane mode where (Ft) counter-balances all the drags.

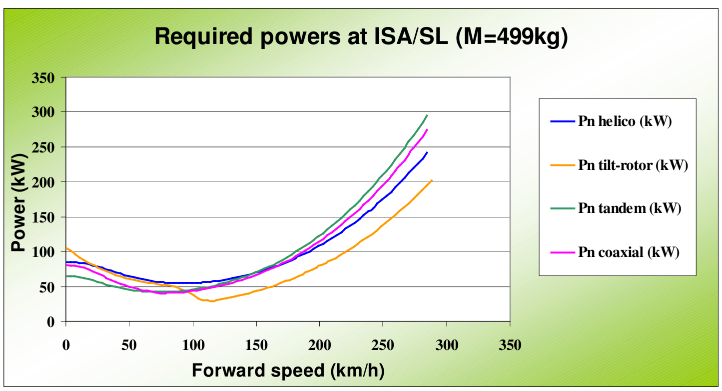

Figure 11 : Comparisons of the needed powers for the coaxial and the equivalent helicopter, tandem, tilt-rotor.

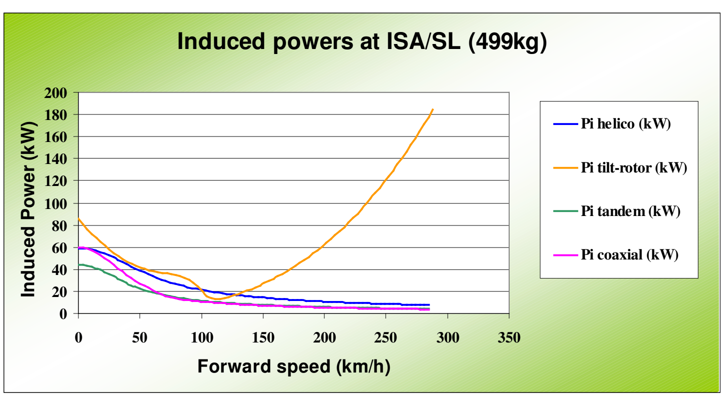

Figure 12 : Comparisons of the induced powers for the coaxial and the equivalent helicopter, tandem, tilt-rotor.

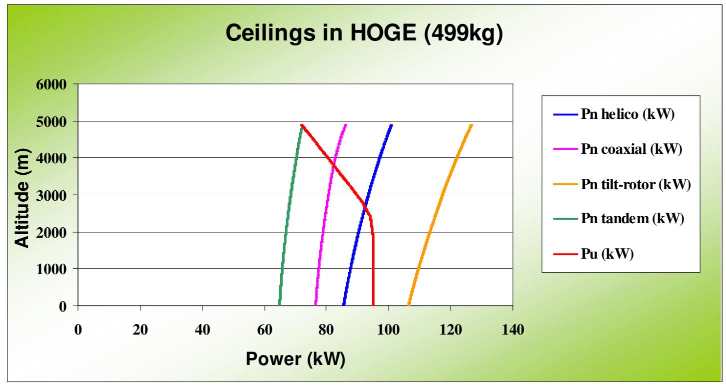

Figure 13 : Comparisons of the HOGE ceilings for the coaxial and the equivalent helicopter, tandem, tilt-rotor.

From Fig. 11, it can be deduced that the tilt-rotor will have a higher ceiling in forward flight (lower minimum needed power). For the HOGE ceiling, the required power is plotted w.r.t. to pressure altitude in ISA condition and compared with the usable power provided by the centurion 1.7 engine (with turbo-effect, Fig. 13). The tilt-rotor requires a more powerful engine, the helicopter has a HOGE ceiling around 2800m, the coaxial around 3900m and the tandem about 4900m.

These trends are well-known, but this simple tool allows to quantify them quickly. Of course several choices are possible for comparing the different rotorcrafts : same total weight or same payload weight, same rotor solidity, … Here we have made the arbitrary choices of comparing the configurations with the same total weight and an equivalent rotor solidity. For the tandem and the tilt-rotor, the empty weights are higher than those of the helicopter and coaxial. Moreover, the comparisons have been done here with the same engine providing the same usable power (Pu). Yet for taking advantage of the tilt-rotor configuration, the (Pu) should be higher. For example the Eagle-Eye uses a turbine engine delivering 313 kW for a maximum gross weight of 1,022 kg. So, that is a rather academic exercise performed for preparing the following more sophisticated simulations.

2ND LEVEL : FLIGHT MECHANICS SIMULATION

ONERA decided to adapt a flight dynamics simulation code to the case of the coaxial configuration for several reasons. As regards the performance assessment, it should be noted that the classical “energy method” used previously provides a rough estimation which does not consider the actual attitude of the rotorcraft which varies with the flight conditions : the pitch and bank angles of the airframe, the tilt of the main rotor, ... More precisely the “energy method” is more or less based on the balance of the forces in the assessment of the power consumption. But there is no comprehensive trim process as done in a flight mechanics code which accounts for : the balance of the forces and moments, as well as for the degrees of freedom of the airframe, rotors, …

Moreover from the performance estimation standpoint, in the previous method the effect of the interferences is taken into account only in the induced power calculation. But obviously, these interferences make the rotors operate in different aerodynamic conditions. That should change the power consumed by the blades airfoils drag.

Therefore, the performance estimation by using a comprehensive flight mechanics simulation code will provide a better assessment of the performances. Furthermore the adaptation of the simulation code for the case of the coaxial will prepare the work for further flight dynamics investigation.

Adaptation of the flight dynamics code

A development version of the H.O.S.T. code (“Helicopter Overall Simulation Tool” e.g. [15]) has been adapted by ONERA for the case of rotorcrafts with two coaxial contra-rotating rotors.

➢ The airframe :

Usually, the HOST code makes use of wind-tunnel test data giving the aerodynamic coefficients of the airframe with respect to the angle attack and sideslip angle.

In the case of the pre-designed CAPECON configurations, these experimental data are not available. Thus the fuselage has been represented by the method of equivalent surfaces. These drag surfaces have been drawn from the CATIA design, (see 3D view in annex of [1]).

The front drag surface is : $Sx_f = 0.615\ m^2$
The lateral drag surface is : $Sy_f = 1.576\ m^2$
The vertical drag surface is : $Sz_f = 1.44\ m^2$
The drag coefficients are assumed to be :
$Cx = Cy = Cz = 1$

The additional drag due to the big rotor mast and hub in the coaxial case is accounted for by adding an extra drag force above the rotorcraft center of gravity. Three data inputs are dedicated to that purpose :

- the equivalent drag surface: $S_{Mast\text{-}Hub} = 0.2m^2$;
- the drag coeffcient : $Cx_{MH} = 1$;
- the vertical position of the point of application of this additional drag force on the rotor mast : $Zc_{MH} = -0.98372$ m (average vertical position of the two rotors above the cG).

➢ The two contra-rotating coaxial rotors :

Following the pre-design described in [1], the two rotors are see-saw rotors, i.e. there is no conicity angle : the average blade flapping angle on one rotor revolution is null. The blades flapping motion lead to the longitudinal (BC) and lateral (BS) tilt angles which may be different on each rotor.

Both rotors are represented by a blade element model taking into account all the data description provided by the pre-design : chord, airfoil, …

Seen from above the upper rotor rotates in the trigonometric sense and the lower rotor in the clockwise sense. A difference with single main rotor helicopters is that the yaw control is performed by making different the opposite torques on the rotors. That leads to change the classical controls setting in the code. But concretely, the pilot still has four controls : the collective DT0, the longitudinal cyclic DTS, the lateral cyclic DTC and the differential collective DDT0.

For the rotor induced velocity field, the user can choose among different model options (e.g. Meijer-Drees model or Pitt and Peters dynamic inflow model). For coaxial, the mean inflow term through each rotor is recalculated by the interference model developed by ONERA and which has been implemented within the flight dynamics code.

Example of results from the simulation

Stabilising effect :

An interesting result of the simulation is that without taking into account the pitch-up moment due to the rotor mast drag, no convergence of the trim algorithm could be found above 160 km/h. In forward flight the rotors thrusts are tilted forward resulting in a pitch down moment. The mast drag compensates that by creating a pitch up moment as does a horizontal stabilizer. With this stabilising effect, the cyclic controls need also less variation for trimming the rotorcraft in forward flights. However, this drag is a corollary of the mast-hub design and can not be tuned as done for a horizontal stabilizer especially conceived for the pitch axis equilibrium. Therefore the results in forward flights depend on this rotor mast drag which, in absence of data, has been approximated in the model with an equivalent drag surface.

Effect on the blade flapping angles :

In forward flights, both rotors longitudinal tilts are in the same direction. The rotors tip path planes are tilted backwards with respect to the rotor mast which is tilted more and more forward due to the helicopter pitch down angle. But, the upper rotor tilts on the right side, whereas the lower rotor tilts on the left side. Yet these lateral tilt angles are limited to a maximum of ~1.6° in steady forward flight at 40 km/h. Even with 2° of lateral tilt that leads to ~9 cm of vertical flapping motion at the blade tips. Therefore on the right side, it remains a blade vertical clearance about :
51 cm – (2 × 9cm) = 33 cm

That indicates that the clearance between the blade tips will remain in a good safety margin for avoiding the collision between the blade tips (verified at least for steady forward flights from hover up to the maximum speed).

Due to the increase of downwash through both rotors in hover and low speeds (below ~60km/h), the required collective angles are then stronger. That increases the blades airfoils drag forces and thus the rotor torques. Hence the required power by each rotor is increased and therefore also the total needed power Wnec.

Comparisons with an equivalent helicopter

Hereafter are presented some comparisons on trim level flights between the coaxial configuration and an equivalent single main rotor helicopter.

The equivalent helicopter has exactly the same characteristics than the coaxial rotorcraft except that :

- it has one main rotor with four blades (instead of two see-saw rotors with two blades),
- it has a tail rotor and a horizontal stabilizer inspired by the Bo105 helicopter case. Their sizes have been determined by using the ratio of the rotor radius : 2.55 / 4.912 = 0.52. Their position have been calculated with the same scaling ratio plus 30 cm rearward in order to insure the clearance between the main rotor and tail rotor blades. The ratio between the main rotor and tail rotor revolution speeds has been applied (~0.19), i.e. the main rotor of the equivalent helicopter turns at 740 rev/min (as for the coaxial) and the tail rotor at 3883 rev/min.

On Fig. 14 are compared the equilibrium curves of the equivalent helicopter and of the coaxial without interferences (red curves) and with interferences (green curves).

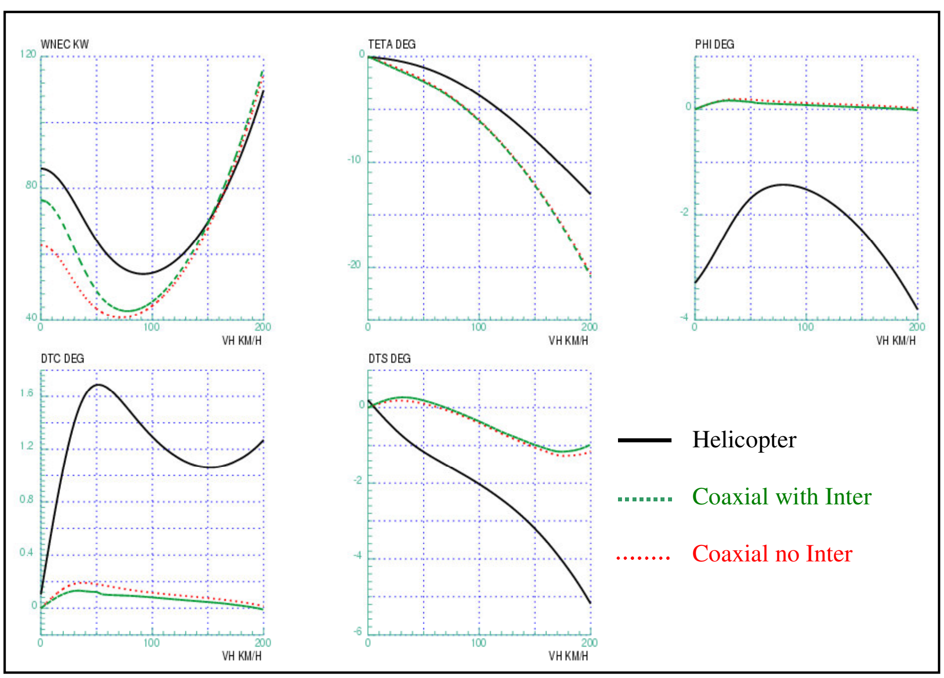

Figure 14 : Trim comparisons between the coaxial (with and without interferences) and the equivalent helicopter.

Compared with the helicopter, the coaxial follows the same tendency on the pitch axis : a pitch attitude (TETA) tilted forward for allowing the forward flight, but with a stronger pitch down. Yet on the lateral axis, the behaviors are different :

- with the helicopter, the bank angle (PHI) follows a shape close to the power curve, because the tail rotor develops a lateral force to compensate the main rotor torque and this lateral force produces a roll moment which is compensated by the lateral tilt of the helicopter ;
- with the coaxial, the bank angle remains weak because the rotors torques compensate each other, this configuration does not need an anti-torque device.

The variations of the cyclic controls (DTC, DTS) with forward speed are lower with the coaxial.

From the performance point of view, it can be seen on Fig. 14, that the required power (WNEC) is lower with the coaxial. The increase of the required power with the forward speed is stronger in the case of the coaxial because of the additional drag due to the bigger mast. But even with that penalty, the required power remains lower than the one required by the helicopter until 170 km/h. That comes from a strong reduction of the required power (the induced power to be more precise) with the coaxial mainly at low speeds.

This result, shown more in detail on Fig. 15, confirms well the previous performance estimation obtained by the energy method. Indeed, in the flight mechanics simulation code, the required power is not determined by the energy method but by summing the consumed power to overcome the torques of the rotors. The required power by a rotor is calculated as the product of the rotor revolution speed and of the torque due to the drag forces along the blades. These local drag forces depend on the Mach number and on the angle of attack of the airfoils. The local angle of attack depends on the local airspeed and on the blade element pitch angle which depends on the controls (collective and cyclic). These control pitch angles are determined (as well as the attitude of the rotorcraft : pitch and roll angles) by the trim algorithm which searches by iteration the balance of the forces and moments.

Therefore the two methods for calculating the required power are different, although they are of course connected since they deal with the same physics.

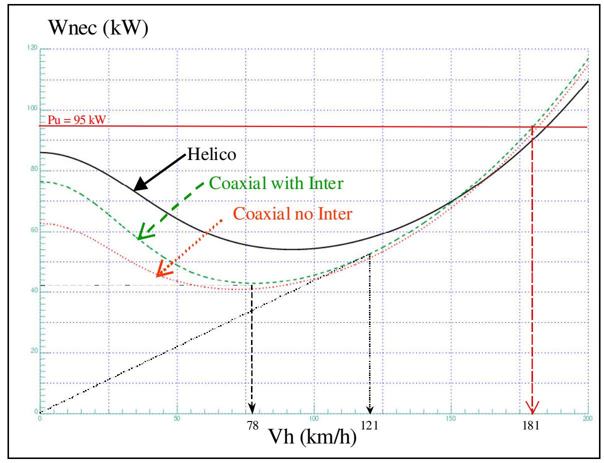

Figure 15 : Power Needed for trim level flights, comparisons between the coaxial (with and without interferences) and the equivalent helicopter.

As mentioned, the performance estimation by the comprehensive simulation code is in principle more realistic because it computes the complete equilibrium of the rotorcraft. The attitude (pitch attitude TETA and bank or roll angle PHI on Fig. 14) and rotor tilt angles are not prescribed (as in the previous assessment by energy method), but they result from the trim process.

The power curves and resulting characteristics speeds match well between the two different tools and methods (analytical assessment with the energy method Fig. 9, and numerical computation with the flight mechanics code Fig. 15), although some differences on the effect of the interferences can be noticed.

For instance in HOGE (M=499kg) :

- For the equivalent helicopter :
  - the flight mechanics code computation provides Wnec = 85.99 kW (Fig. 15)
  - the analytical assessment (Fig. 9) gives 85.435 kW.

- For the coaxial :
  - The flight mechanics code estimations (Fig. 15) are :
    no interferences : Wnec = 62.79 kW,
    with interferences : Wnec = 76.517 kW
  - The analytical assessment (Fig. 9), gives :
    without interaction : 62.38 kW,
    with interferences : 80.529 kW.

The flight mechanics code assessment of the required power (with interferences) in hover is ~4kW lower than the analytical one. That may comes from the fact that in the analytical calculation, the aerodynamic rotor interaction is taken into account only in the induced power assessment (P_i) and not for the blade airfoils drag power (P_p). In the comprehensive flight mechanics computation, the changes of the rotors inflow affect the blade local airspeeds and thus the blade airfoils angles of attack, which make vary their drag and the blade pitch control for trimming the rotorcraft.

In forward flight, there is no more significant effect of the interferences above around 75 km/h. The total required power for the coaxial and the equivalent helicopter by both methods match well. Yet it can be noticed that the required power increases a little quicker with the forward speed in the computation of the flight mechanics code. For example with the analytical energy method assessment, the required power is around 90 kW at about 180 km/h, whereas with the flight mechanics calculation the 90 kW are required at 175 km/h. That could be due to the pitch attitude (TETA) which becomes more and more negative for allowing the forward flights in the flight mechanics computation (see Fig. 14) and thus the fuselage drag is increased, compared with the analytical approximation where the pitch angle remains a flat null attitude whatever the forward speed.

3RD LEVEL : MISSION SIMULATION

In a third step, a tool has been settled for assessing the stabilized performances on an entire mission. The flight mechanics simulation model has been implemented in a more general program for computing the performances on the different parts of a complete mission profile including : hover, climb, cruse, descent, loitering flight, …

Performances calculation on a mission profile

The H.O.S.T. simulation code can not be used directly for that purpose. The trim computations are usually done at one flight point or for a sweep on one parameter (forward or vertical speed, altitude, etc.). The flight dynamics simulations are mostly done on a short time duration allowing to consider a constant rotorcraft mass.

A MatLab program has been built which reads the mission characteristics and performs the calculation in two main loops. The outer loop iterates on the different steps of the mission (hover, cruse, climb, etc.). The inner loop iterates until the convergence on the mass of consumed fuel on each step. The flight mechanics code is called at each iteration for computing the required power for trimming the rotorcraft at each flight condition (mass, altitude, temperature, horizontal and vertical speed). The rotorcraft mass is recalculated at each iteration taking into account the consumed fuel mass depending on the required power, the pressure, the temperature and the time duration of this mission step. The fuel flow is calculated with respect to the specific consumption the engine (here the Centurion 1.7) and to the flight point.

In climb and descent, the flight conditions are considered at the average altitude between the beginning and end of the step. Another inner loop has been added for truncating each mission step into smaller sub-steps better accounting for the variation of the flight conditions especially on the long duration steps.

Example of mission profile

The mission profile is defined by the initial flight condition (altitude, temperature, mass, etc.), the number of steps and for each step :

- the variation of altitude,
- the horizontal flown distance,
- the horizontal speed,
- the time duration of the step.

This last data (duration) can not always be deduced from the horizontal speed and horizontal distance, for example in case of hover or vertical flight.

Here again many choices are possible for defining the missions. In the example presented hereafter, the configurations are compared when hovering during the same time and flying the same horizontal and vertical distances. In hover, the time duration has been fixed arbitrarily. The cruses are performed at the best endurance speed (Vbe). In descent, the duration of the step has been calculated from the imposed horizontal distance and with a horizontal speed giving a time such that :

$$|V_z| / v_{i0} \leq 0.4$$

where (v_{i0}) is the mean inflow in hover. That has been done for avoiding the vortex ring state occurring at high descent rate. In climb, the duration is calculated from the fixed horizontal distance and from the horizontal speed imposed at the Vbe (minimum power). The climb rate is therefore a consequence of these choices.

The mission profile presented here could correspond to a typical "search in mountains mission" in agreement with the survey of potential applications performed in CAPECON [1]. It includes eleven steps (Fig. 16) : a hover (HOGE), a cruse, a climb, a second cruse, a descent, a hover~low speed flight and the same way back.

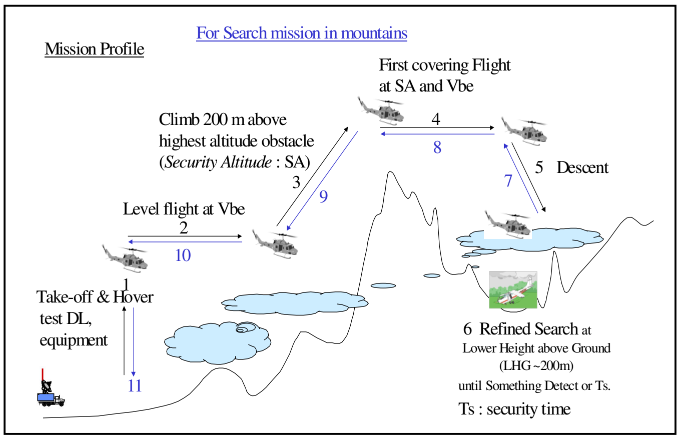

Figure 16 : Typical mission profile with 11 steps.

Example of results

The CAPECON coaxial and the equivalent helicopter have been compared on a typical mission as described previously including eleven steps for a total of 89.6 km.

First the horizontal speeds have been chosen at the respective (Vbe) for each configuration (at ISA/SL) : 21 m/s for the coaxial and 25 m/s for the helicopter.

The powers required by the coaxial are then lower than the ones of the helicopter for each steps. But for a mission defined in such a way, the fuel consumption is yet higher with the coaxial : the total fuel consumption is 41.64 kg for the coaxial and 39.27 kg for the helicopter. Indeed, except for the hovering flights for which the flight times are the same, the flight times for covering the same distances are longer with the coaxial because the chosen forward speeds are lower than those of the helicopter : the total mission time is 1h28min39s for the coaxial and 1h16min37s for the helicopter.

A second comparison is presented hereafter when imposing to the coaxial to perform the mission with exactly the same conditions as done previously by the helicopter : same forward speeds chosen at the helicopter Vbe (25 m/s at ISA/SL), same climb and descent rates, …

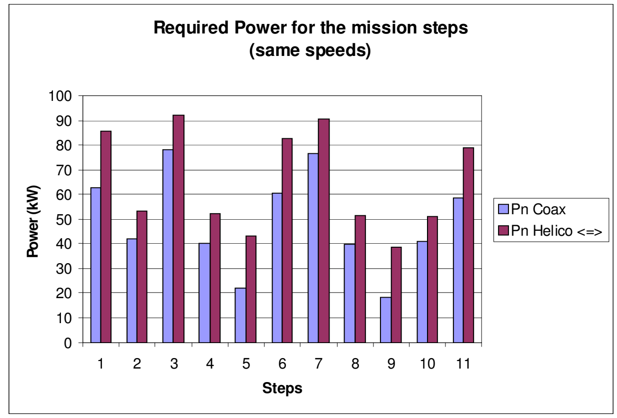

Figure 17 : Required powers for the two configurations flying the mission in the same conditions.

The required powers are once again lower for all the mission steps with the coaxial (Fig. 17). Both configurations covering the mission with the same flight times, the fuel consumption of the coaxial is now lower than the one of the helicopter (Fig. 18).

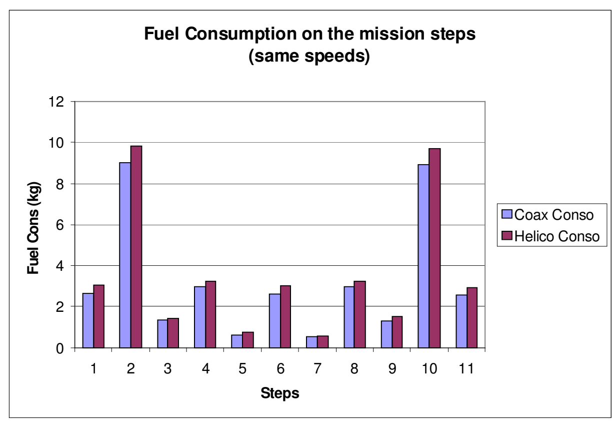

Figure 18 : Fuel consumption of the two configurations flying the mission in the same conditions.

The total fuel consumption of the coaxial for performing the mission (89.6 km) in 1h16min37s is 35,37kg, i.e. 67% of the initial fuel (52.5kg) instead of 75% in the helicopter case.

That kind of tool could be used in the design phase, but also in a operational context for preparing a mission. For example, the speeds can be adjusted depending on the priorities : endurance, range, urgency, …

Conclusions

A new rotor inflow model for coaxial has been implemented in the following simulation tools.

Three levels of tools for assessing the RW-UAV performances have been presented :

- the analytical calculation by the energy method,
- the flight mechanics computation (H.O.S.T.),
- the performance assessment on a mission profile.

Examples of comparisons between different RW-UAV configurations have been shown. The stabilized performances of the coaxial CAPECON configuration have been compared with those of equivalent : helicopter, tandem twin-rotors and tilt-rotor concepts. It must be underlined that it is not the purpose of this paper to say what is the best configuration. It depends of course highly on the type of missions. Moreover, it is also a wider multi-disciplinary problem involving consideration of technology maturity, safety, cost, handling qualities, … This paper is focused on the presentation of methods for quantifying the stabilized flight mechanics performances. The effect of different rotor arrangements (one main rotor, two rotors one above the other, two side by side tilting rotors, two separated fore-aft rotors) have been investigated.

These tools can also be applied to full-scale rotorcrafts. The studied UAVs within CAPECON being of gross weight around 500 kg, their sizes are such that no Reynolds number effect has been considered in a first approach. Such adaptation of the models could be envisaged for further studies of smaller RW-UAVs.

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