Further development of a rotary-wing preliminary design tool

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Abstract

The objective of this work is to further develop an open-source tool dedicated to the analysis of the performance of rotary-wing aircrafts to be used for their preliminary design. Under this scope, the possibility to study compound helicopters has been added to the tool, including the two main compound configurations: helicopter with a wing and with a propeller. Strip Theory and Thin Airfoil Theory have been used to model the wings and Blade Element Momentum Theory has been applied to analyse the propellers. The consequences of the interaction between the helicopter rotor and the compound elements (wing and propeller) have been analysed in detail. Besides the inclusion of this new functionality in the tool, the calculations of simple helicopter configurations have also been completed with the addition of the ground effect. Moreover, a different tool dedicated to the analysis of cyclocopters has been created. The validation and verification of the tool is done and some case studies are presented to ensure the reliability of the analysis developed.

Keywords: compound helicopters, Strip Theory, Thin Airfoil Theory, Blade Element Momentum Theory, cyclocopters, preliminary design.

1. Introduction

The goal of this work is to further develop a tool (originally created within another student's project [1]) whose aim is to work as an open-access and easy Matlab tool for the user to perform some calculations that can provide information about the initial design of rotary-wing aircraft. With its intuitive interfaces, it can be useful for aerospace designers who want some initial information about their vehicles to make some decisions for future steps, students or people who are just interested in the topic. Therefore, the objective of this work is to complete this tool by adding new functionalities, which are related to the study of compound helicopters' performance. In addition to these new functionalities for the helicopters studies, the creation of a new interface for cyclocopters' performance calculations (based on the codes developed in another student's project [2]) is also under the scope of this work.

Conventional helicopters only use rotors to generate these forces and they are suitable for many kinds of flight operations. However, auxiliary systems can be added to the conventional configuration to improve helicopters performance in specific operations or flight regimes. Compound helicopters use auxiliary structural elements, such as wings, or propulsion devices, such as propellers, to improve the aircraft performance. One of the main improvements that compound helicopters configurations can usu-

ally achieve is an increase in helicopter maximum flight speeds. There are three main kinds of compound helicopters configurations, depending on the auxiliary elements they use. [3]

The first kind of configuration is the lift compound helicopter, which has a fixed wing added to the airframe. This wing creates lift, so that it carries a fraction of the aircraft weight, therefore offloading the main rotor (it has to generate now a lower vertical thrust to overcome the weight). Moreover, the addition of the wing often decreases the power required by the main rotor for a certain flight operation, due to this offloading and the usual high aerodynamic efficiency of such wings. [3]

The second compound helicopter configuration is the propulsive compound helicopter. In this configuration, one or more propulsive devices, like propellers, are added to the conventional helicopter model at the tail or wings. The propellers create thrust, so that they carry a fraction of the aircraft total drag, therefore offloading the main rotor (it has to generate now a lower horizontal thrust to overcome the drag). This main rotor offload also reduces the rotor power requirements, which leads to a reduction of the shaft torque and rotation speed needs. This allows the helicopter to reach higher velocities, since the onset of retreating blade stall and compressibility effects in the main rotor are now delayed to higher velocities. [4]

Both previous configurations are usually combined to make compound helicopters which have both wings and propellers and combine characteristics of both configurations.

In conclusion, compound helicopters are useful when flying at high forward velocities. Their main disadvantages are related to their higher empty weights when compared to conventional configurations, which implies higher costs for carrying a specific payload, and their higher aerodynamic complexity. [3]

Cyclocopters are a specific type of rotary-wing drones. A cyclocopter is a rotary-wing system whose blades move parallel to the rotation axis. The angle of attack of each blade cyclically varies according to the mechanism placed on the rotation axis, so that the blades have positive and negative angles of attack at upper and lower positions of each cycle, respectively. The resultant required force of the cyclocopter and its required power are obtained by varying the angle of attack amplitude and phase angle of each cycle. [2]

2. Theoretical background

2.1. Wing model

In order to study the wing's performance and, specially, its interaction with the main rotor through two different approaches to compare the results afterwards, two different theories were developed: Strip Theory and Thin Airfoil Theory. The user of the tool can choose which theory to use to make the calculations.

2.1.1. Strip Theory

In this theory, which is described in detail in [3], the wing is divided in some strips or slices along the wingspan. In each slice, the aerodynamic forces and moments are calculated to finally integrate the results in all the slices and obtain the resultant wing's forces and moments.

First, the velocity component in the reference horizontal direction, U_T, and the velocity component in the reference vertical direction, U_P, have to be calculated. Their values will depend on the helicopter speed and the main rotor wake, in case it is interfering with the flow over the wing. Then, the angle of attack is:

$$\alpha = \theta + \theta_{twist} - \phi \qquad (1)$$

being θ the fixed incidence angle of the wing (pitch angle), θ_{twist} the twist corresponding to the slice in study and ϕ the inflow angle.

Having the information of the angle of attack, the lift and drag coefficients of each slide are obtained using the information of the lift and drag polar curves of the corresponding airfoils. And the lift and drag of each slide have the following expressions in compressible regime:

$$dL = \frac{1}{2}\,\rho\,U^2\,c\,C_l\,/\sqrt{1-M^2} \qquad (2)$$

$$dD = \frac{1}{2}\,\rho\,U^2\,c\,C_d\,/\sqrt{1-M^2} \qquad (3)$$

where ρ is the density, c is the chord, U is the total velocity that the slice sees and M is the Mach number.

Once the lift and drag are calculated for all the slices, they are all integrated along the wingspan to obtain the resultant lift and drag of the wing.

2.1.2. Thin Airfoil Theory

In the cases where the airfoil is thin enough and the angle of attack is not so far from zero, Thin Airfoil Theory can be used to study the airfoil performance. This theory, which is described in detail in [5] simulates the aerodynamic properties of an airfoil with vortex sheets.

Depending on the helicopter geometry, rotor and wing characteristics and flight conditions, there are three possible situations for the wing with respect to the rotor wake: wing totally outside the wake, wing totally inside the wake and wing partially inside the wake. When the incident velocity changes in a point which is between the airfoil leading and trailing edge, like in case the main rotor wake is partially hitting the wing, the point in x-axis where the wake starts hitting the wing, $x = c_{inside}$, must be calculated and transformed to a polar system:

$$\theta_0 = arccos\left(1 - 2\frac{c_{inside}}{c}\right) \qquad (4)$$

The angle of attack and the total velocity are calculated using the following expressions:

$$\alpha = A_0 + \frac{A_1}{2} \qquad (5)$$

$$U = \sqrt{U_\infty^2\,(1 + tan^2(\alpha))} \qquad (6)$$

where U_∞ is the flight velocity. The coefficients are calculated using the following expressions [4]:

$$A_0 = \frac{w}{U_\infty}\left(\frac{\theta_0}{\pi} - 1\right) \qquad (7)$$

$$A_1 = -\frac{2}{\pi}\frac{w}{U_\infty}sin(\theta_0) \qquad (8)$$

being w the main rotor wake velocity that hits the wing.

With the information of the angle of attack and the total velocity, the lift and drag of the wing can be calculated. For the lift coefficient, the following expression is used:

$$C_l = 2\,\pi\,(\alpha - \alpha_{ZL}) \qquad (9)$$

where α_{ZL} is the zero-lift angle of attack of the airfoil.

The strips' drag coefficients are directly obtained from the drag polar curves of the corresponding airfoils and the final wing performance is studied in the way described in section 2.1.1.

2.2. Propeller model

To model the propeller and calculate its performance in forward flight, the Blade Element Momentum Theory with the induction factors method is applied. The Blade Element Momentum Theory integrates the Momentum Theory, which describes a mathematical model of an ideal actuator disk, and Blade Element Theory, which analyzes the local events taking place at the actual blade, by dividing them into a number of strips or slices and assuming that each blade section acts as a 2D airfoil to generate forces.

This theory methodology, which is described in detail in [6], requires an iterative process where the iteration variables are the axial and radial induction factors, a and a', respectively. These factors are defined in the following way:

$$a = \left(\frac{4 sin^2(\phi)}{\sigma C_n} + 1 \right)^{-1} \qquad (10)$$

$$a' = \left(\frac{4 sin(\phi) cos(\phi)}{\sigma C_t} - 1 \right)^{-1} \qquad (11)$$

where ϕ is the inflow angle, C_t and C_n are the tangential and normal force coefficients, respectively, and σ is the propeller solidity.

The velocity seen by a blade element has an axial component and a tangential component:

$$U_a = (1 - a)U_\infty \qquad (12)$$

$$U_t = (1 + a')\omega r \qquad (13)$$

where U_∞ is the helicopter velocity, ω is the propeller rotation speed and r is the radial component of the blade element.

These velocity components are graphically represented in Figure 1, where $V_0 = U_\infty$ and $V_{rel} = U$ and there is no twist.
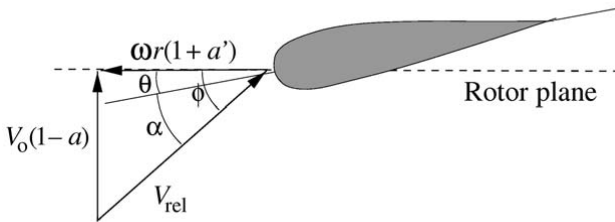

Figure 1: Aerodynamic environment at a propeller blade element [6, pg. 47]

Knowing the angle of attack, the lift and drag coefficients for the blade element are taken from the polar curves of the corresponding airfoil. Then, by rotating airfoil lift and drag, the tangential and normal forces (the components of the total blade force which are parallel and perpendicular to the rotor plane, respectively) are calculated and thus, their coefficients:

$$C_n = C_l \, cos(\phi) + C_d \, sin(\phi) \qquad (14)$$

$$C_t = C_l \, sin(\phi) - C_d \, cos(\phi) \qquad (15)$$

The definition of these normal and tangential forces coefficients are:

$$C_n = \frac{p_N}{\frac{1}{2} \rho \, U^2 \, c} \qquad (16)$$

$$C_t = \frac{p_T}{\frac{1}{2} \rho \, U^2 \, c} \qquad (17)$$

The induction factors can be now computed through their definitions to continue with the iterative process.

When the convergence is achieved, with the angle of attack and the velocity, the lift and drag of the blade element are calculated. Additionally, the thrust and torque of the blade element are:

$$dT = dL \, cos(\phi) - dD \, sin(\phi) \qquad (18)$$

$$dQ = [dL \, sin(\phi) - dD \, cos(\phi)]r \qquad (19)$$

The total blade element power is composed of two different sources of power:

Induced power:

$$dP_i = dL \, sin(\phi) \, r \, \omega \qquad (20)$$

Profile power:

$$dP_0 = dD \, cos(\phi) \, r \, \omega \qquad (21)$$

Once these parameters of all the blades elements are calculated, they are integrated. Finally, an average of these values in all the azimuthal positions which have been considered is made to reach the final values of the propeller thrust and power.

2.3. Ground effect

The ground effect describes the fact that the thrust of a helicopter rotor increases as it approaches the ground. When flying in hover or at low forward velocities, the ground effect may be beneficial, since a relevant power reduction is experienced. However, the power increases as the helicopter starts flying faster because of the flow recirculation at the leading edge of the rotor disk and its consequent increase of the induced flow at high forward velocities. In order to mathematically account

for the ground effect in forward flight, the following expression is used to correct the thrust [7]:

$$T_{IGE} = \frac{T_{OGE}}{1 - \frac{1}{16}\left(\frac{R}{Z}\right)^2 \left[\frac{1}{1+\left(\frac{U_\infty}{v_i}\right)^2}\right]} \quad (22)$$

where R is the rotor radius, Z is the helicopter altitude, U_∞ is the forward flight velocity and v_i is the rotor induced velocity.

3. Software implementation

Six specific tools have been created or completed using Matlab functionality *appdesigner*. Three of the tools that take part in this work correspond to basic tools, where the calculations are easier, the study is not so deep and more simplification assumptions are made. These three tools address the following topics: conventional helicopters, axial helicopters and tandem helicopters. Other two tools correspond to detailed tools, where the calculations are more complex, the study is deeper and less simplification assumptions are made (so the calculations and their results are closer to reality). These two tools address the following topics: conventional helicopters and coaxial helicopters. The last tool created is the one that studies cyclocopters. In this case, only the tool interface (and its corresponding layout code) was developed, since the codes which the calculations are based on have been developed as part of a different project. The ground effect has been added to all the calculations performed by the detailed tools. The factor presented in Equation 22 has been applied to the thrust calculated by the codes to get the actual thrust in ground effect.

3.1. Main rotor wake interferences
3.1.1. Interaction of the wake with the wing

The expressions for the velocities in the horizontal and vertical reference direction (in pure forward flight) are different depending on whether the main rotor wake, w, is interfering with the wing or not. In case they are in contact, these expressions are:

$$U_p = w \cdot sin\left(\chi + \alpha_{TPP}\right) \quad (23)$$

$$U_t = U_\infty + w \cdot cos\left(\chi + \alpha_{TPP}\right) \quad (24)$$

being U_∞ the helicopter flight velocity, χ the wake angle and α_{TPP} the main rotor tip path plane angle with respect to the incident velocity direction.

The wake angle, χ, is defined as the angle between the edge of the main rotor wake and the direction which is perpendicular to the rotor. This angle, together with some other geometrical parameters, is illustrated in Figure 2.

Looking at Figure 2, c_{inside} can be calculated, using geometrical considerations, with the following expression [4]:
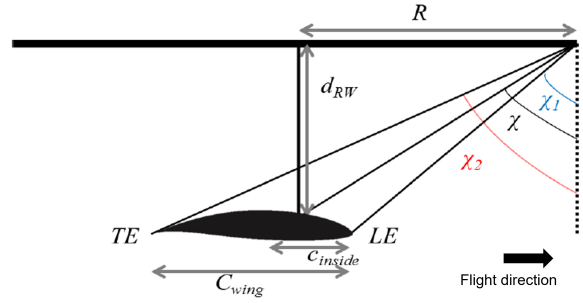

Figure 2: Geometrical parameters involved in the interaction between the main rotor wake and the wing. [4, pg. 36]

$$c_{inside} = tan(\chi + \alpha_{TPP})\,d_{RW} - R + \frac{c_{wing}}{4} - h_{RW} \quad (25)$$

where d_{RW} and h_{RW} are the vertical and horizontal distances between the main rotor rotation axis and the wing aerodynamic centre (which is approximated to zero in Figure 2), respectively.

The way of calculating the main rotor wake velocity, w, to model the aerodynamic download on the wing due to its proximity to the rotor is the following:

$$w = k\,v_i \quad (26)$$

where v_i is the mean induced velocity of the main rotor disc and k is an empirical factor. This factor is one of the tools' inputs, so it is chosen by the user. However, a value of $k = 1.5$ is set as the default one to match the 10% download in hover that was measured in an experimental testing of the V-22. [3]

Another effect of this interaction between these two elements is that the wing experiments a downward force because of the main rotor wake hitting its upper surface. This force, f_d, uses the drag coefficient corresponding to a flat plate perpendicular to the flow and the vertical component of the wake velocity:

$$f_d = \frac{1}{2}\rho\left(c - c_{inside}\right)\left[w \cdot sin\left(\chi + \alpha_{TPP}\right)\right]^2 \cdot 1.28 \quad (27)$$

Another consequence of the proximity of the rotor and the wing to be taken into account is the pseudo ground effect experimented by the rotor because of the wing existence. [7] To model this effect, Equation 22 is used.

3.1.2. Interaction of the wake with the propeller

When the helicopter flies in forward flight regime, the wake of the main rotor is pushed back, so it will reach the propeller located at the tail or, at least, a part of it. This phenomenon becomes especially

remarkable when the forward flight velocity is significantly high, since the wake angle would be high as well and then the wake will move almost horizontally towards the helicopter tail, reaching the propeller in a more probable way.

It has been considered that the only part of the rotor wake which the propeller sees and interacts with is its horizontal component. Consequently, the expression which is actually used for the propeller axial component is the sum of the flight velocity and the horizontal component of the wake velocity, corrected by the axial induction factor. Therefore, the actual equation used in the Blade Element Momentum Theory of the propeller calculations to account for this rotor-propeller interaction is the following one:

$$U_t = (1 + a')[\omega r + w \, sin(\chi)] \qquad (28)$$

3.2. Basic tool

Conventional helicopter

The first of the tabs created is used to perform the calculations about the conventional lift compound helicopters, and its layout can be seen in Figure 3.

In this tab, the user introduces the flight conditions, the wing characteristics, the airfoil that the wing uses and fills some other fields related to calculation parameters. After that, the button *Calculate* is pressed to perform the calculations. When they are finished, the outcome of the calculations is shown in the results panel, where the user can see the wing lift and drag, the rotor mean thrust, power and torque and the rotor blade root pitch angle.

The second tab is dedicated to the propulsive compound helicopters calculations. The different fields this tab includes generally follow the structure of the previous tab, but there are some differences due to the characteristics of this new helicopter configuration.

The third and last tab of this tool is dedicated to the analysis of those helicopters that combine both compound configurations, i.e. they have a wing and a propeller. In this case, there are less panels and editable fields in the layout. This is because this last tab takes the geometrical and aerodynamic characteristics of the wing and the propeller from the data introduced in the previous two tabs.

Coaxial helicopter

The second of the basic tools created is used to perform the calculations of coaxial compound helicopters, i.e. the helicopter with two rotors (one above the other), no tail rotor and the compound device (wing, propeller or both).

The structure of this tool is basically the same as in the conventional helicopter tool: the first tab created is for the lift compound helicopter, the second one is for the propulsive compound helicopter and the third one is for the combined compound configuration. The fields inside each tab are basically the same as in the conventional helicopter tool, with the exception of the fields which show the specific results of the top and bottom rotors.

Tandem helicopter

The third of the basic tools created is used to perform the calculations of tandem compound helicopters, i.e. the helicopter with two rotors (one at the front and the other one at the rear part of the vehicle), no tail rotor and the compound device (wing, propeller or both). Its structure regarding the different tabs and fields inside them is basically the same as in the conventional and coaxial helicopter tools.

3.3. Detailed tool

The detailed tools have the same main structure that the basic tools have, but they are more complex because of the following specific aspects:

- The wing and propeller geometrical characteristics (chord and airfoil) may vary along the wingspan. Furthermore, the wing is divided into two different sections where the chord evolution and airfoil selection may be different.

- The wing may have twist: the user may choose between a constant, linear or parabolic evolution for the twist.

- Both the Strip Theory and the Thin Airfoil Theory may be used.

- The wing tip losses are modelled, so the lift is not constant along the wingspan.

- The main rotor wake interference with the wing and the propeller is modelled.

- The ground effect and the pseudo ground effect induced by the wing are considered.

- For the lift compound helicopter configuration, the possibility of including just one semi-wing in the vehicle (the wing structure is only at one of the helicopter sides) is included.

Conventional helicopter

The first of the tabs created is used to perform the calculations about the lift compound helicopters.

In this tab, the user firstly introduces the flight conditions. In the wing chord distribution panels, the user specifies the geometrical distribution of the chord along the wingspan (constant, linear or parabolic) and introduces the chord values at both limits of each section in which the wing has been divided. The percentage of the semi-wingspan at which the section change occurs is also submitted. In a similar way, in the wing twist distribution panel, the pitch distribution must be specified, as
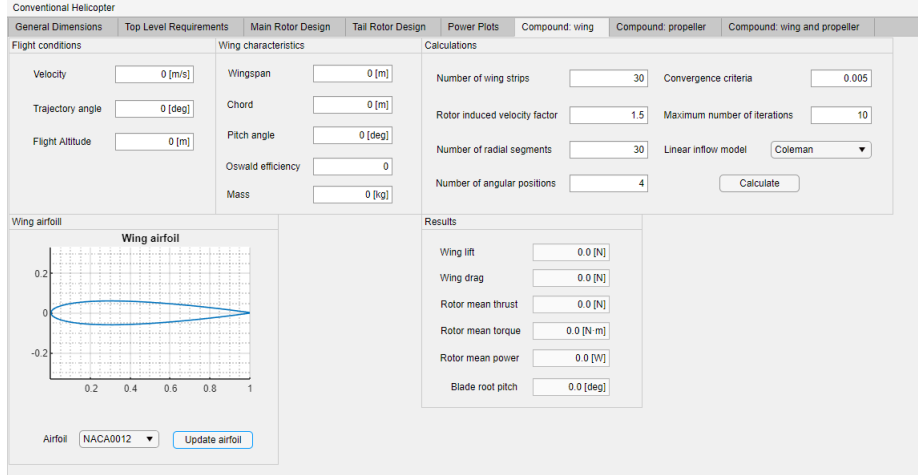
Figure 3: Lift compound configuration tab of the conventional helicopter basic tool

well as the pitch at the wing tip (since it is assumed to be zero at the root). There is another panel where the airfoil that each section in which the wing is divided uses is specified. In the wing characteristics panel, further wing properties, which are necessary for the detailed calculations, are defined. After these wing properties fields, the user fills some fields related to some calculation parameters. After that, the button *Calculate* is pressed to perform the calculations. When they are finished, the outcome of the calculations is shown in the results panel, where the user can see the wing lift and drag, the rotor mean thrust, power and torque. Moreover, the collective, cyclic longitudinal and cyclic lateral pitch angles are also shown in this panel, as well as the tail rotor collective.

The second tab is dedicated to the propulsive compound helicopters calculations. The different fields this tab includes generally follow the structure of the previous tab, but there are some differences due to the characteristics of this new helicopter configuration.

The third and last tab of this tool is dedicated to the analysis of those helicopters that combine both compound configurations. This last tab takes the geometrical and aerodynamic characteristics of the wing and the propeller from the data introduced in the previous two tabs.

Coaxial helicopter

The second of the basic tools created is used to perform the calculations of coaxial compound helicopters.

The structure of this tool is basically the same as in the conventional helicopter tool, as well as the fields inside each tab, with the exception of the fields which show the specific results of the top and bottom rotors. In order to illustrate that, the lift compound tab is shown in Figure 4.

Besides the creation of these new tabs on the detailed tools, the codes corresponding to the calculations in the first tabs of these detailed tools (originally developed as part of another project) have also been completed, by adding the ground effect. Therefore, the calculations of the simple (no compound) helicopter performance of the detailed tools take into account the thrust increase that the main rotor experiments due to the vehicle proximity to the ground. This has been modelled by applying the factor presented in Equation 22 to the main rotor thrust value that these codes calculate.

3.4. Cyclocopter tool

The last tool created under the scope of this work is dedicated to make the calculations to study the performance of the cyclocopter. This tool is composed of three different tabs: Single Rotor: hover performance, Single Rotor: forward flight performance and Cyclocopter: pitch calculation.

The first tab which appears when the tool is opened analyses the performance of a single rotor of the cyclocopter in hover. Its layout may be seen in Figure 5. First, the user introduces some specific characteristics of the rotor in study. In the second panel, the flight conditions are set. Once these initial characteristics have been set, the user must choose the theory which the calculations are going to be made with: sinusoidal pitch variation or four-bar linkage mechanism system. There are two different panels, each of them dedicated to one of the theories.

If the theory chosen is sinusoidal pitch variation, the pitch amplitude and the maximum pitch angle must be set as calculation parameters. Similarly, if the theory chosen is four-bar linkage mechanism system, the constants L_2, L_3 and L_4 (which are characteristic of this theory) must be set as calculation parameters. [2] After that, the correspond-
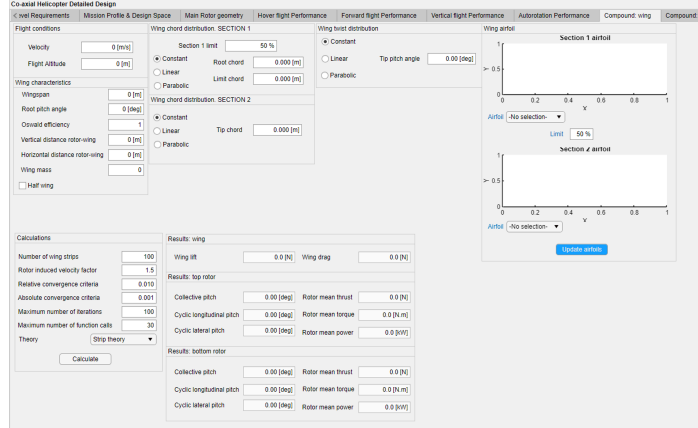
Figure 4: Lift compound configuration tab of the coaxial helicopter detailed tool

ing button *Calculate* must be pressed to perform the calculations and visualize the result below: the thrust and power of the rotor under the introduced conditions are shown.

The second tab analyses the performance of a single rotor of the cyclocopter in forward flight, which includes the same content as the first one.

Once the calculations for a single rotor have been made, the third and last tab of this tool analyses the whole cyclocopter, integrating the action of all its rotors. The first panel (cyclocopter characteristics) is used to select the cyclocopter properties. It includes the same fields as in the previous tabs (the ones corresponding to the single rotor properties) plus the number of rotors, the cyclocopter weight and the cyclocopter flat plate area, which are characteristics of the full cyclocopter and are necessary for computing the total thrust that the vehicle must develop for performing the selected flight.

Then, the tab is divided in two different parts, related to the hover and forward flight performance. The user must introduce some parameters which are necessary for the iterative process that is included in the calculations method: top and bottom limits for the pitch angle amplitude and the thrust convergence tolerance. Basically, the code applies the sinusoidal pitch variation theory, trying all the values for the pitch amplitude included in the defined interval and setting as the final result the one that produces a value for the total thrust whose difference with the necessary thrust for the selected flight conditions is under the specified tolerance. Once the calculations have finished, the rotors pitch amplitude, thrust and power are shown below.

4. Validation and Verification
4.1. Wing

For the wing codes validation and verification, a wing of some determined properties has been selected and introduced in the tool wing code. Then,

the same wing has been modelled in *xflr5* [8] and the results obtained have been compared with the tool ones. The results have been obtained using the wing code of the detailed tool. For that, a tapered wing (whose chord decreases from root to tip) has been analysed. The properties of the selected wing are the following ones: wingspan of 6 m, chord of 0.8 m at the root and 0.5 m at the tip, no twist (constant pitch angle equal to 0º) and NACA0012 as constant airfoil. The calculations have been performed for several values of the flight trajectory angle and the results are shown in Table 1.

Table 1: Comparison of lift and drag results of a tapered wing obtained from wing code of detailed tool and *xflr5*

Trajectory angle (º)	Lift (N)		
	Code	xflr5	Difference
$\theta_{traj} = 2$	1804.2	1682.9	6.7%
$\theta_{traj} = 7$	6217.6	5851.0	5.9%
Trajectory angle (º)	Drag (N)		
	Code	xflr5	Difference
$\theta_{traj} = 2$	64.9	58.7	9.6%
$\theta_{traj} = 7$	219.0	185.9	15.1%

4.2. Propeller

The propeller code of the detailed tools has been tested by modelling a propeller with a more complex geometry. For this study, a real commercial propeller has been modelled, whose name is *APC Sport Propeller 11x4*. Its geometrical parameters, obtained from [9], have been introduced. The thrust and power results of the code have been compared with the APC experimental data included in [9] and they are presented in Table 2, for different values of the rotation and flight speeds.
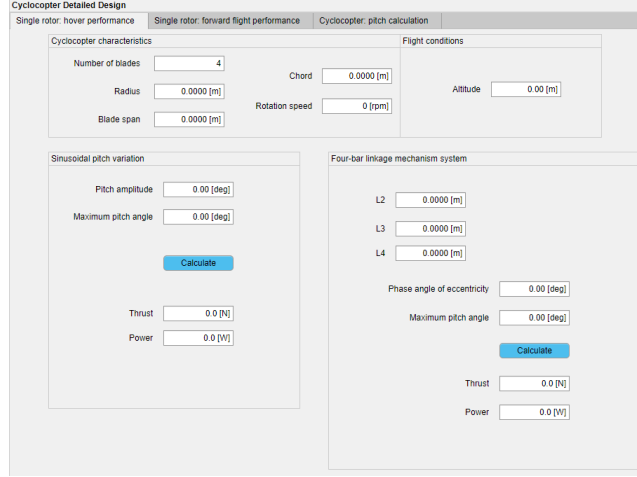
Figure 5: Single rotor hover performance tab of the cyclocopter tool

Table 2: Comparison of thrust and power results of APC Sport propeller 11x4 obtained from propeller code with experimental data

Rotation	Velocity	Thrust (N)			Power (W)		
(rpm)	(mph)	Code	APC	Error (%)	Code	APC	Error (%)
1000	5	0.049	0.053	8.21	0.14	0.00	-
2000	9.1	0.24	0.28	14.23	1.31	1.49	12.48
3000	15	0.44	0.49	9.95	3.84	5.22	26.50
4000	20.1	0.77	0.87	11.40	9.01	11.93	24.46
5000	25	1.22	1.37	10.66	17.76	23.12	23.17
6000	30	1.76	1.98	10.96	30.69	38.78	20.85
7000	35	2.40	2.71	11.44	48.74	59.66	18.30

4.3. Lift compound helicopter

In order to analyse how the contact with the main rotor wake affects the wing lift when it is partially inside the wake, the wing detailed code has been run independently of the rest of the tool codes to manually vary the percentage of the wing root section chord which is inside the rotor wake. The vertical distance between both elements and the flight velocity have not been changed, but the wing percentage have been artificially varied. For that, a standard wing similar to the ones of the previous studies have been used. The results of wing lift, using both theories, have been represented, as a function of the percentage inside the wake, in the same graph to be compared and it can be seen in Figure 6.

The wing detailed code has been run to calculate the wing lift for several angles of attack and constant airfoils (of different thickness), using both theories to compare the results (since the Strip Theory is considered valid for all the airfoils). The wing chosen for this study has the following geometrical characteristics: wingspan of 10 m and chord of 1.5 m. The flight velocity is set to 30 m/s. The results can be seen in Table 3.

Finally, the whole tool structure has been used to calculate the main rotor power of a real lift compound helicopter. The helicopter which is going to be used to validate the lift compound helicopter tab of the tools is Sikorsky S-67. The rotor power has been calculated for a range of flight velocities to be compared with the experimental data included in Roche's article [4]. A graphical representation has been made and it can be seen in Figure 7.

4.4. Propulsive compound helicopter

The whole propulsive compound helicopter tool structure has been used to calculate the main rotor power of a real compound helicopter. The helicopter which is going to be used is Lockheed AH-56 Cheyenne, which is in fact a combined compound helicopter, since it includes a wing and a propeller at its tail. The rotor power has been calculated for a range of flight velocities to be compared with the experimental data included in Johnson's report [10]. A graphical representation has been printed in the same graph where the experimental data is presented, and it can be seen in Figure 8.

After all these studies have been analysed, a good

Table 3: Comparison of wing lift results of Thin Airfoil Theory and Strip Theory, for different angles of attack and airfoils

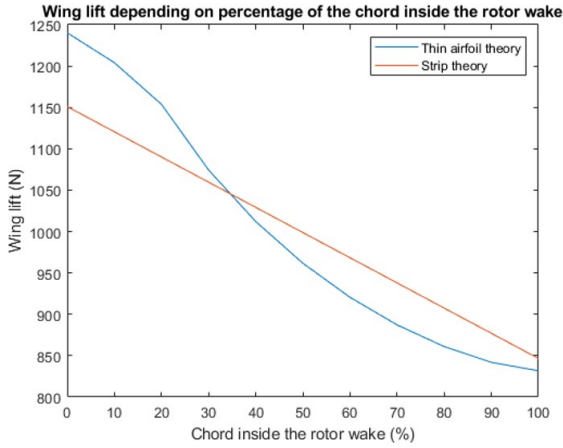| AoA (º)	Airfoil	Wing lift (N)		Error (%)
		Strip theory	Thin airfoil theory	
2	NACA 0012	1372.1	1347.1	1.9
	NACA 0018	1388.1	1347.1	3.0
	NACA 0022	1375.2	1347.1	2.1
	NACA 0030	1152.9	1347.1	-14.4
	SC 1095	1908.9	1847.4	3.3
10	NACA 0012	6864.9	6735.5	1.9
	NACA 0018	6594.7	6735.5	-2.1
	NACA 0022	6404.9	6735.5	-4.9
	NACA 0030	5601.5	6735.5	-16.8
	SC 1095	7361.2	7235.8	1.7

Figure 6: Variation of wing lift with the percentage of the root section chord which is inside the rotor wake
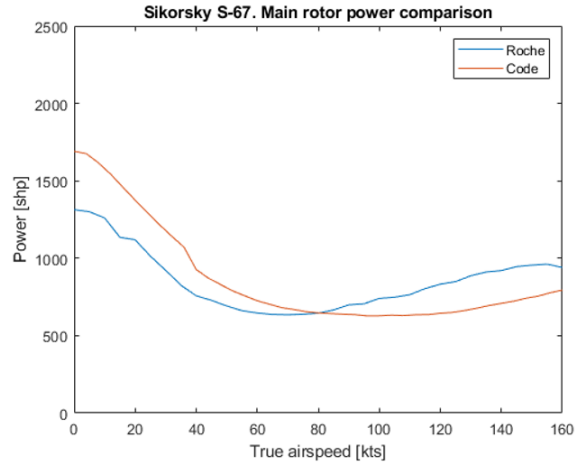

Figure 7: Comparison of the evolution of rotor power with flight speed obtained from tool results (red line) with experimental data (blue line) of Sikorsky S-67

agreement has been found between the different theories and experimental data, which allows the validation of the the wing and propeller codes independently and also the lift, propulsive and combined compound helicopter codes. Therefore, it can be concluded that the methodologies used in this project to study compound helicopters are adequate.

5. Conclusions

The developments done in this work have represented a relevant improvement in terms of tool complexity, have broadened its possibilities and increased the depth of the study it develops. The tools developed in this work should be used for the preliminary design of rotary-wing vehicles, since they are useful to get a first approximation of the performance of the vehicle in design. However, they also have some limitations, so they should not be the definitive tool to base on for developing a complete design. The tools in this work are useful to get a good starting point on which to base the next stages of the vehicle design.

After analysing the results obtained about compound helicopters performance, it can be concluded that the addition of a wing improves the helicopter performance in flight conditions implying high forward velocities, but its efficiency decreases as flight speeds decrease or the helicopter goes into axial flight. A more careful study must be done to analyse the efficiency of a propeller, since a trade-off between its help to the main rotor propulsion and the additional power it requires must be reached. The efficiency of the compound helicopters, especially in case of the propulsive compound configuration, depends on the helicopter characteristics and flight conditions, so it is important to deeply analyse the mission and objectives of the vehicle to
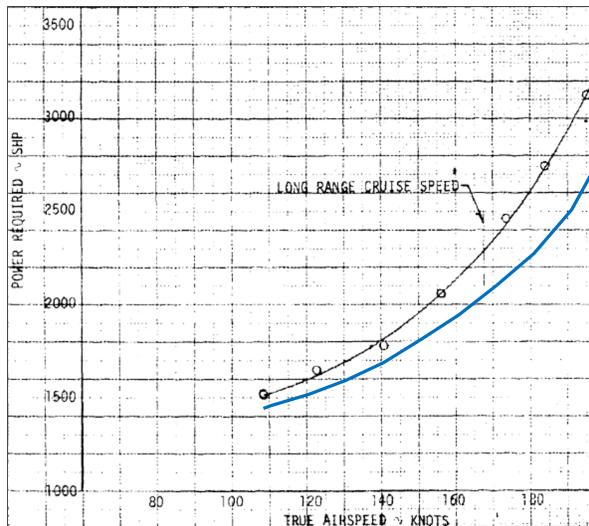
Figure 8: Comparison of the evolution of rotor power with flight speed obtained from tool results (blue line) with experimental data (black line) of Lockheed AH-56 Cheyenne. [10, pg. 98]

decide if the addition of a wing and/or a propeller to the helicopter is convenient.

One of the main advantages of the tools developed is their possibility to quickly determine the feasibility of whatever rotary-wing vehicle solution the user thinks of, as well as the possibility of comparing some different designs in order to determine which one is more efficient or matches the user interests. This is done in a quick and visual manner, since not many parameters are necessary to perform the study and they are introduced in the different tabs in a very intuitive way. The reliability, versatility and open-source nature of these tools make them attractive for students' analysis and people interested in developing the first stages of large design projects.

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