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VTOL UAV – A Concept Study

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Thesis Work Conducted at CybAero AB

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Abstract

This thesis deals with the development of a Conceptual Design Tool for unmanned helicopters, so called VTOL UAVs. The goal of the Design Tool is:

- Quick results
- Good accuracy
- Easy to use

The two first points of the goal are actually more or less dependent on each other. In almost all cases a high accuracy gives a slow calculator and vice versa. In order to fulfill the goal a compromise between calculation accuracy and calculation time needs to be done.

To make the Design Tool an easy to use program a graphical user interface is used. The graphical user interface allows the user to systematically work his way thru the program from a fictive mission to a complete design of a helicopter. The pre-requirements on the user have been eliminated to a minimum, but for the advanced user the possibilities to create more specific and complex helicopters are good.

In order to develop a Conceptual Design Tool the entire helicopter needs to be seen as a complete system. To see the helicopter as a system all of the sub parts of a helicopter need to be studied. The sub parts will be compared against each other and some will be higher prioritized than other.

The outline of this thesis is that it is possible to make a user friendly Conceptual Design Tool for VTOL UAVs. The design procedure in the Design Tool is relatively simple and the time from start to a complete concept is relatively short. It will also be shown that the calculation results have a good agreement with real world flight test data.

Acknowledgements

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Daniel Moëll Joachim Nordin

Contents

List of figures

Nomenclature

a	lift curve slope
a_0	coning angle
a_{1s}	longitudinal flapping angle
A	rotor disc area
A_1	longitudinal flapping
A_b	blade area
b	number of blades
b_{1s}	lateral flapping angle
B	tip loss factor
B_1	lateral flapping
c	chord
c_c	chordwise force coefficient
c_f	skin friction coefficient
c_n	normal force coefficient
c_s	spanwise force coefficient
C_d	drag coefficient
C_l	lift coefficient
C_m	moment coefficient
C_H	force coefficient in x-direction
CM_{yM}	main rotor moment coefficient in y-direction
CM_{xM}	main rotor moment coefficient in x-direction
C_P	power coefficient
C_Q	torque coefficient
C_T	thrust coefficient
C_Y	force coefficient in y-direction
D	drag
D	rotor disc diameter
D_{ind}	induced drag
D_p	parasitic drag
D_v	vertical drag
e	hinge offset
f	equivalent front flat area
g	gravity
h	distance between c.g. and main rotor
h_T	distance between tail rotor and main rotor
H	force in x-direction
H	altitude
I_b	blade moment of inertia
K	constant
l	length
L	lift
L	temperature lapse rate
m	mass
$\dot{m}$	mass flow
M_{yM}	main rotor moment in y-direction
M_{xM}	main rotor moment in x-direction
M_b	static moment of blade around the flapping hinge
M_A	aerodynamical moment
$M_{C.F}$	centrifugal moment

M_W	moment due to weight
p	static pressure
P	engine power
q	dynamic pressure
Q	torque
r	radius station along the blade
R	gas constant
R	rotor radius
Re	Reynolds's number
S	projected area
T	thrust
T	temperature
T_T	tail rotor thrust
U	resultant velocity at disc
U_b	total blade velocity
U_P	perpendicular blade velocity
U_R	radial blade velocity
U_T	tangential blade velocity
v_i	induced velocity
V	forward speed
V	volume
V_C	climb speed
w	induced rotor wake velocity
W	weight
W_r	rotor work
W_w	rotor wake work
$x_{c.g}$	c.g. offset in x-direction
$y_{c.g}$	c.g. offset in y-direction
Y	force in y-direction
α	angle of attack
α_s	shaft angle of attack
α_{TPP}	tip path plane angle of attack
β	flapping angle
β_s	fuselage tilt
γ	blade lock number
δ_3	pitch-flap coupling angle
θ	blade pitch angle
θ_0	collective pitch
θ_1	linear twist
λ	inflow ratio
μ	tip speed ratio
ρ	density of air
σ	solidity
ϕ	inflow angle
ψ	Azimuth angle
Ω	rotational speed of rotor

Abbreviations

CAD	Computer Aided Design
CFD	Computational Fluid Dynamics
COTS	Commercial Off-The-Shelf
FEM	Finite Element Method
G.W.	Gross Weight
ISA	International Standard Atmosphere
MR	Main Rotor
MRD	Main Rotor Diameter
MTOW	Maximum Take-Off Weight
OEW	Operational Empty Weight
RPM	Revolutions Per Minute
SFC	Specific Fuel Consumption
TBO	Time Between Overhaul
TR	Tail Rotor
UAV	Unmanned Aerial Vehicle
VBScript	Visual Basic Scripting Edition
VTOL	Vertical Take-Off and Landing

1st Chapter Introduction

In aircraft design the work is usually divided into three major phases starting with the conceptual design phase. During the conceptual design phase relatively simple methods and tools are used to do feasibility studies on a large number of designs with the goal to roughly define which design that best meet the requirements on the aircraft.

The next phase is preliminary design where one or a couple of designs from the conceptual phase are studied in more detail. A lot of analysis and simulations are conducted with the aim to completely define the helicopter and its characteristics.

If the previous two phases were successful and the helicopter is to be manufactured the final phase called the detailed design phase is started. In this phase the aircraft and all of its components are completely defined in detail.

1.1 Goal

The goal of this thesis is to develop an easy to use computer based tool for conceptual design studies on small unmanned single rotor helicopters, so called VTOL UAVs. The tool is intended for VTOL UAVs up to a maximum weight of 500kg. The work is done on behalf of CybAero AB in Linköping.

1.2 Methodology

In the initial phase of the thesis most time was spent collecting information regarding helicopter dynamics and conceptual design. Also a database of statistics from other UAV helicopters and a database of available engines on the market were put together.

The next phase was to penetrate the collected theory and sort out the parts that could be applied to this thesis. In order to create the Design Tool a software for graphics and a software for calculations had to be chosen. As it turned out it was convenient to use the same software for both graphics and calculations. The software chosen was Scilab version 4.1.2 [8]. For lift and drag calculations over an airfoil the software XFOIL [10] was used.

When the theory was worked thru and it was figured out how all of the softwares were working the next step was to implement everything in Scilab.

The final part of the thesis was to evaluate the Design Tool against real flight data. Also the robustness of the Design Tool was evaluated.

1.3 The Company

CybAero develops and manufactures UAVs and related sensor systems. Each system is built to meet customer specifications for civilian or military applications.

Although CybAero got its formal start in 2003, the research and development for the company's technology began in 1992 via a joint research project between The Swedish National Defense Research Agency (FOI) and Linköping University.

The headquarters of CybAero is located in Linköping, Sweden with local offices in Abu Dhabi, United Arab Emirates and in Stamford, Connecticut, USA.

2nd Chapter
Theory

In this chapter two different methods for calculating the performance of the helicopter will be discussed. The methods handle the theory behind hover, climb, forward flight and combinations of climb and forward flight. The theory in this thesis does not deal with sideward flight.

2.1 General Theory

Before getting in to equations of how the helicopter is moving it is necessary to understand the basics of how the helicopter works. In flight dynamics it is common to use a body fixed coordinate system, i.e. the coordinate system is fixed relative to the aircraft.

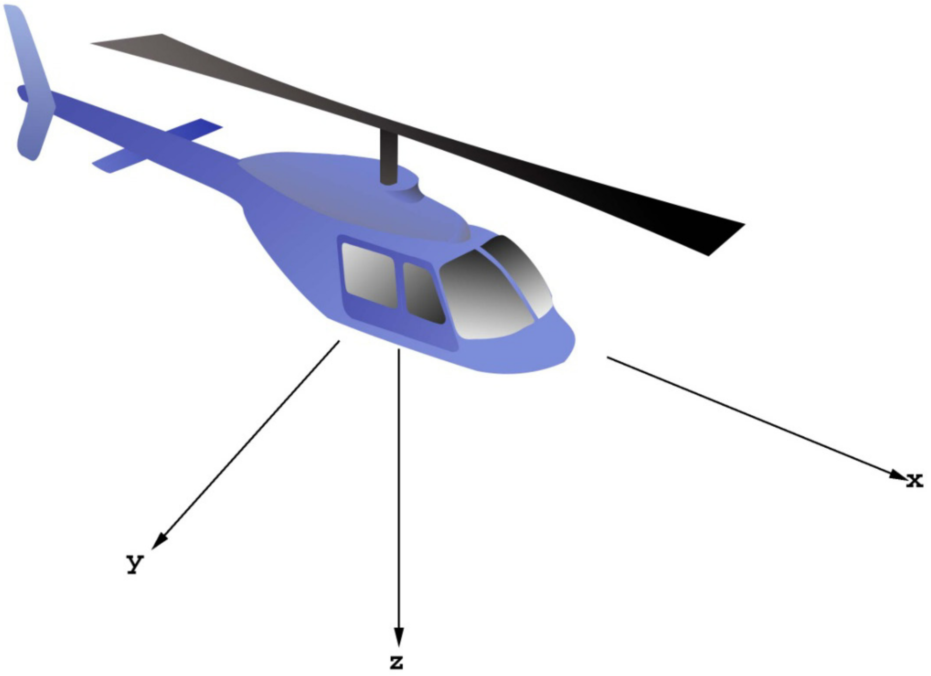


Figure 2-1. Coordinate system

Since the aircraft is moving thru the air it's convenient to define the rotation of the axes such as:

Rotation of x-axis: Roll

Rotation of y-axis: Pitch

Rotation of z-axis: Yaw

Usually a helicopter has one main rotor and one tail rotor. The main rotor's task is to provide enough lift to carry the weight of the helicopter and to provide enough thrust to overcome the drag of the helicopter in forward flight. The tail rotor's task is to balance the torque produced by the main rotor but also to provide control in yaw. To be able to control the helicopter a swashplate is used. The swashplate, located at the rotor shaft, consists of one fixed plate and one rotating plate connected to the blades. The plates can be moved up, down and be tilted.
By moving the plates up and down the pitch of all of the blades will be changed equally and the lift will increase or decrease without roll or pitch movements, this is called collective pitch.

By tilting the swashplate the pitch will locally increase or decrease, the result is control in roll and pitch for the entire helicopter, this is called cyclic pitch.

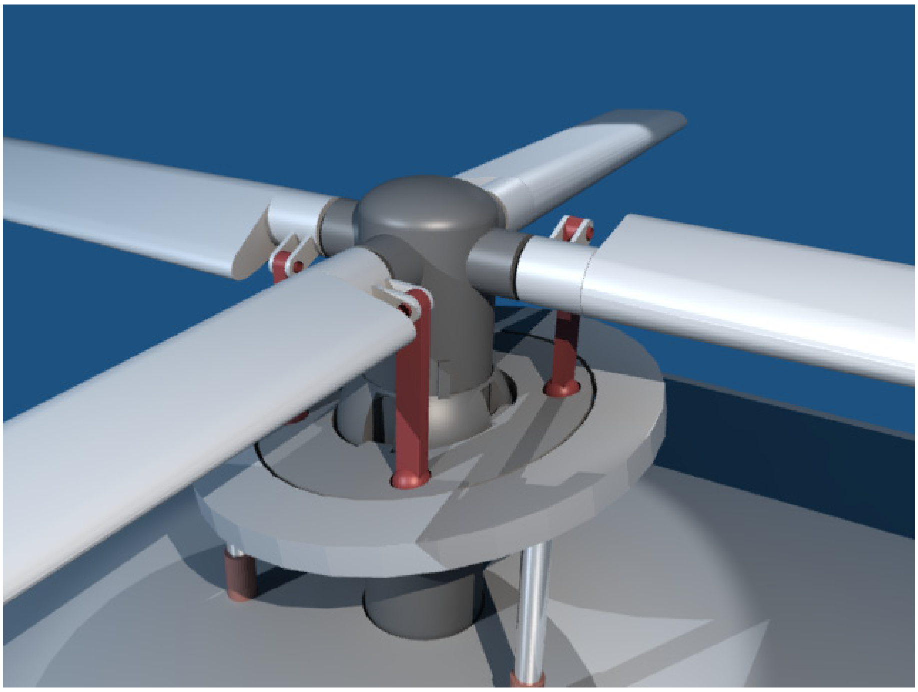


Figure 2-2. Example picture of a swashplate

Just like airplanes, nondimensional coefficients are frequently used in helicopter engineering. The advantage of this is that the rotor characteristics become independent of the rotor size. The three main parameters in helicopter dynamics are Thrust, Torque and Power. They can be nondimensionalized as, Prouty [3]:

$$Thrust\ Coefficient, C_T = \frac{T}{\rho A\,(\Omega R)^2} \tag{2.1.1}$$

$$Torque\ Coefficient, C_Q = \frac{Q}{\rho A\,(\Omega R)^2 R} \tag{2.1.2}$$

$$Power\ Coefficient, C_P = \frac{P}{\rho A\,(\Omega R)^3} \tag{2.1.3}$$

But since $P = Q\Omega$

$$C_P \equiv C_Q \tag{2.1.4}$$

The reference area in the above equations is the rotor disc area, but it is often desirable to have the actual blade area instead. Therefore the ratio between the blade-area and the rotor disc is defined as *solidity*

$$\sigma = \frac{A_b}{A} = \frac{bcR}{\pi R^2} = \frac{bc}{\pi R} \tag{2.1.5}$$

The nondimensionalized coefficients can now be written:

$$C_T/\sigma = \frac{T}{\rho A\sigma\,(\Omega R)^2} \tag{2.1.6}$$

$$C_Q/\sigma = \frac{Q}{\rho A\sigma\,(\Omega R)^2 R} \tag{2.1.7}$$

$$C_P/\sigma = \frac{P}{\rho A\sigma\,(\Omega R)^3} = C_Q/\sigma \tag{2.1.8}$$

Another useful parameter in aerodynamics is the Reynolds's number. The Reynolds's number is the ratio between inertial forces and viscous forces and it defines the flow conditions. The Reynolds's number is defined as:

$$Re = \frac{\rho V l}{\mu} \tag{2.1.9}$$

Where ρ is the air density, V is the air speed, l is the characteristic length and μ is the dynamic viscosity of the air.

2.1.1 The Helicopter in Equilibrium

Like every other system the helicopter follows the laws of physics and has one equilibrium state for every flight condition. The following forces and moments acts on the helicopter in flight:

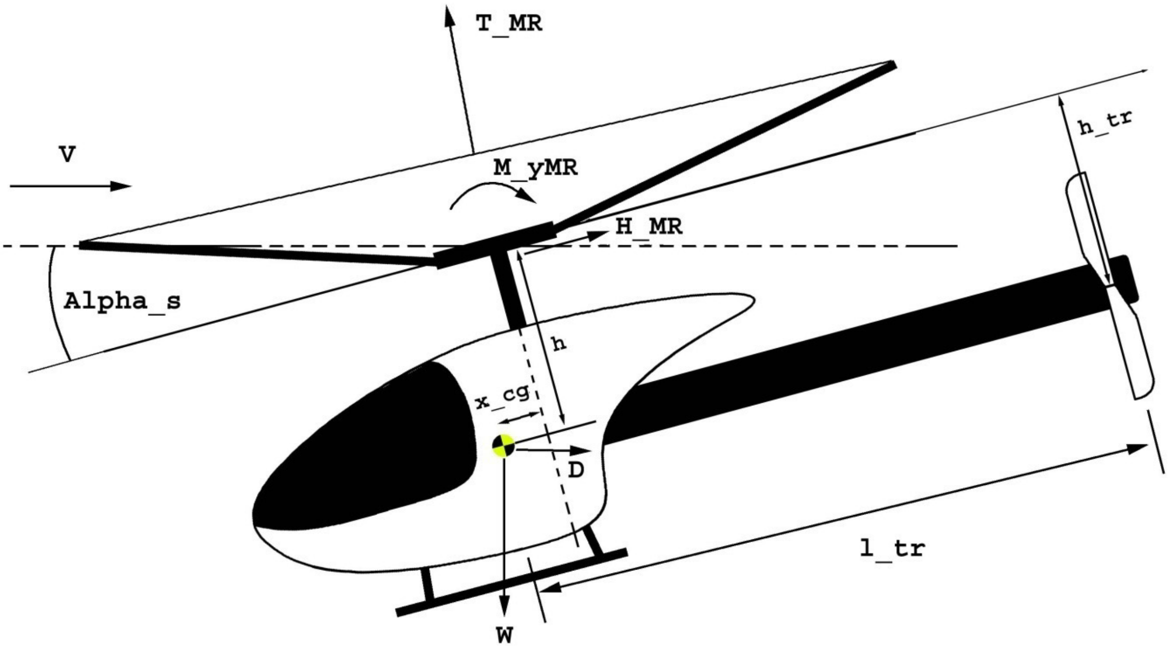


Figure 2-3. The forces and moments acting on the helicopter in longitudinal direction

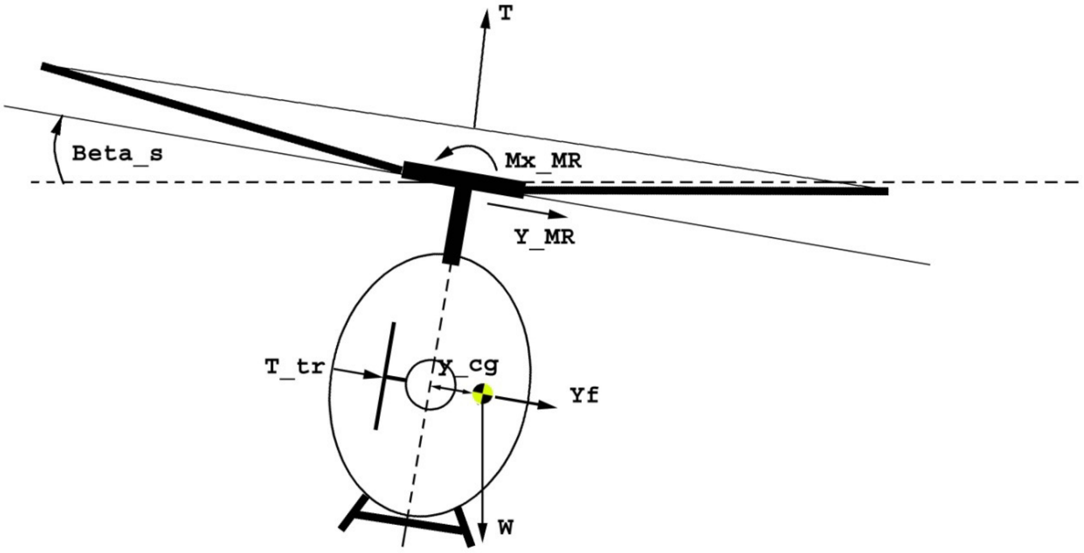


Figure 2-4. The forces and moments acting on the helicopter in lateral direction

The equilibrium states can now be stated in each direction. In vertical direction, Leishman [2]:

$$W - T_M \cos\alpha_s \cos\beta_s + D_v - H_M \sin\alpha_s + Y_M \sin\beta_s = 0 \tag{2.1.10}$$

Equilibrium in longitudinal direction:

$$D_p + H_M \cos\alpha_s - T_M \sin\alpha_s \cos\beta_s = 0 \tag{2.1.11}$$

Equilibrium in lateral direction:

$$Y_M \cos\beta_s + T_T \cos\beta_s + T_M \cos\alpha_s \sin\beta_s = 0 \tag{2.1.12}$$

Equilibrium in Pitch:

$$M_{yM} - W\left(x_{cg} \cos\alpha_s - h \sin\alpha_s\right) - D_p\left(h \cos\alpha_s + x_{cg} \sin\alpha_s\right) = 0 \tag{2.1.13}$$

Equilibrium in Roll:

$$M_{xM} + T_T h_T + W\left(h \sin\beta_s - y_{cg} \cos\beta_s\right) = 0 \tag{2.1.14}$$

Equilibrium in Yaw:

$$Q_M - T_T l_T = 0 \tag{2.1.15}$$

All the different parameters above are defined in Section 2.2 and Section 2.3.

2.2 Momentum Method

The momentum method is based on the conservation of momentum. Newton stated that:

Force = mass * acceleration

In the case of an airplane the total lift-force is equal to the weight of the airplane. The same goes for a single rotor but instead of lift-force the rotor thrust is used. The rotor thrust is:

Rotor Thrust = Mass flow per second * change in flow velocity

Where the change in flow velocity is the difference between the velocities under the rotor and far above it. In the momentum theory all air velocities are assumed to be evenly distributed.

2.2.1 Hover

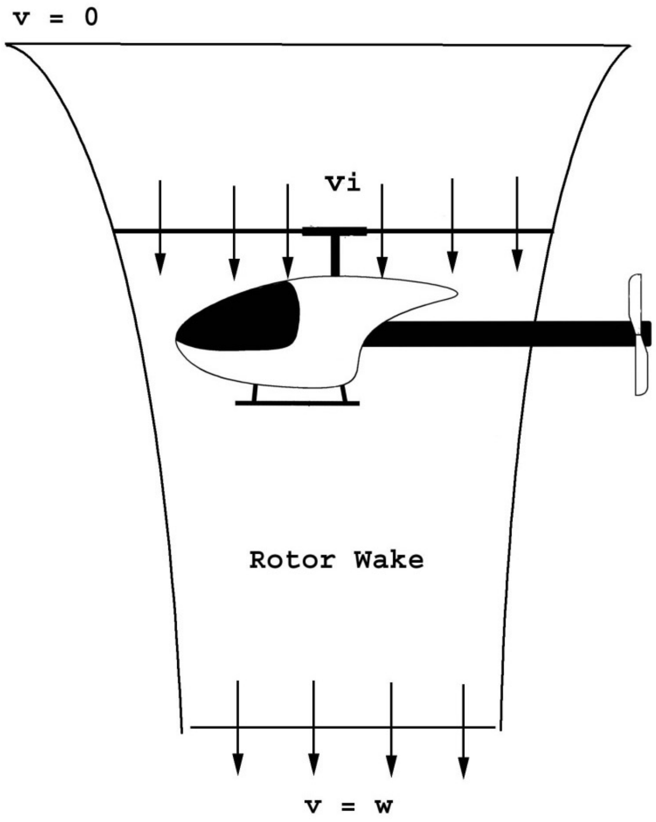


Figure 2-5. The mass flow thru the rotor in hover

Since the airflow far above the rotor is zero in hover, the difference in velocity far above the rotor and under the rotor is equal to the velocity under the rotor. The mass flow is the net mass flow thru the rotor and is defined by:

$$\dot{m}_1 = \rho v_i A \tag{2.2.1}$$

Where v_i is the induced air velocity thru the rotor. The rotor thrust can now be written as:

$$T = \rho v_i A \cdot \Delta v = \rho v_i A w \tag{2.2.2}$$

In the momentum theory the rotor and the rotor wake are considered to be a closed system and therefore the work of the rotor and the work of the rotor wake must be the same. The work done by the rotor can be expressed:

$$W_r = Force \cdot Velocity = Tv_i = \rho v_i^2 Aw \tag{2.2.3}$$

The work produced by the wake is the total change in kinetic energy of the wake and can be described as:

$$W_w = \frac{1}{2}\dot{m}_2 w^2 \tag{2.2.4}$$

Due to the law of conservation the mass flow at the rotor and the mass flow in the wake must be the same and therefore:

$$W_w = \frac{1}{2}\dot{m}_2 w^2 = \frac{1}{2}\dot{m}_1 w^2 = \frac{1}{2}\rho v_i A w^2 \tag{2.2.5}$$

Since the rotor work and the rotor wake work are the same:

$$\rho v_i^2 Aw = \frac{1}{2}\rho v_i A w^2 => w = 2v_i \tag{2.2.6}$$

Substituting equation 2.2.6 in equation 2.2.2 gives:

$$T = 2\rho v_i^2 A \tag{2.2.7}$$

Equation 2.2.7 gives:

$$v_i = \sqrt{\frac{T}{2\rho A}} \tag{2.2.8}$$

When air is flowing around the helicopter fuselage a vertical drag occurs. The drag can be calculated by using the general drag equation:

$$D = C_d q S \tag{2.2.9}$$

Where C_d is a drag coefficient depending on the cross-sectional shape of the fuselage, q is the local dynamic pressure and S is the projected area of the fuselage. $C_d S$ is often called the equivalent front plate area, i.e. the equivalent area of a flat plate, and can be estimated by use of handbooks. The vertical drag is the component of drag due to induced velocity and climb velocity, or simply vertical flow around the fuselage. The vertical drag can then be expressed as:

$$D_v = C_d S \frac{1}{2}\rho v_i^2 \tag{2.2.10}$$

For a hovering helicopter in equilibrium the rotor has to produce enough thrust to overcome the helicopter gross-weight and the vertical drag, the total amount of thrust is then:

$$T = G.W. + D_v \tag{2.2.11}$$

The minimum power required to produce the required thrust is:

$$P_{Main} = P_{0_{Main}} + T_{Main}\, v_i \tag{2.2.12}$$

The total power required for the entire helicopter also depends on the tail rotor power. The tail rotor balances the torque produced by the main rotor and its power is therefore proportional to the thrust produced by the main rotor. The thrust required balancing the main rotor and the power to produce the thrust is:

$$T_{Tail} = \frac{P_{Main}\, R_{Main}}{(\Omega R)_{Main}\, l_{Tail}} \tag{2.2.13}$$

$$P_{Tail} = P_{0_{Tail}} + \frac{P_{Main}\, R_{Main}}{(\Omega R)_{Main}\, l_{Tail}} v_{i_{Tail}} \tag{2.2.14}$$

If the assumption of no further power-losses is made the minimum total power required is:

$$P_{tot} = P_M + P_T \tag{2.2.15}$$

2.2.2 Vertical Climb

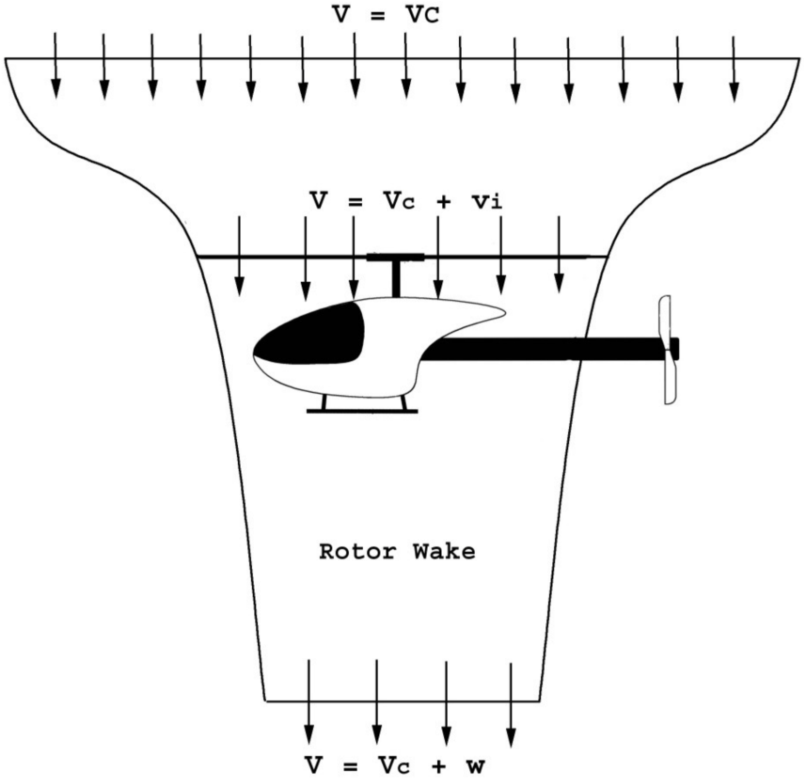


Figure 2-6. The mass flow thru the rotor in climb

The theory in vertical climb is basically the same as in hover except that the vertical velocity, $V_{C,}$ needs to be accounted for. The mass flow thru the rotor is now:

$$\dot{m}_1 = \rho A(v_i + V_c) \tag{2.2.16}$$

The change in velocity over and under the rotor wake is still w since V_C appears both over and under the rotor. The rotor thrust is then:

$$T = \rho A(v_i + V_C) \cdot \Delta v = \rho A(v_i + V_C)w \tag{2.2.17}$$

Just as in hover the work produced by the rotor and the work produced by the rotor wake has to be the same and therefore:

$$\rho A(v_i + V_C)^2 w = \frac{1}{2}\dot{m}_1(w + V_C)^2 - \frac{1}{2}\dot{m}_1 {V_C}^2 = \frac{1}{2}\rho A(v_i + V_c)w(w + 2V_C)$$

$$\Leftrightarrow (v_i + V_C) = \frac{1}{2}(w + 2V_C) \Leftrightarrow w = 2v_i \tag{2.2.18}$$

The thrust equation can now be written:

$$T = 2\rho A(v_i + V_C)v_i \tag{2.2.19}$$

And the induced velocity can be expressed:

$$v_i = \frac{-V_C}{2} + \sqrt{\left(\frac{V_C}{2}\right)^2 + \frac{T}{2\rho A}} \tag{2.2.20}$$

The vertical drag in vertical flight is basically the same as in hover, except that the parts of the helicopter outside of the rotor wake are also contributing to the drag, the drag equation can be written as:

$$D_v = C_d S \frac{1}{2}\rho(v_i + V_C)^2 + C_d S_2 \frac{1}{2}\rho(V_C)^2 \tag{2.2.21}$$

Where v_i is the induced climb velocity, S_2 is the area outside of the rotor wake and C_d is dependent of the shape of the body.

The total power required is higher than in hover, mainly because of the change in potential energy but also because the tail rotor must handle a bigger torque from the main rotor. The power required for the main rotor is:

$$P_{Main} = P_{0_{Main}} + T_{Main}(v_i + V_C) \tag{2.2.22}$$

The minimum total power required for vertical climb is:

$$P_{tot} = P_{0_{Main}} + T_{Main}(v_i + V_C) + P_{0_{Tail}} + \frac{P_{Main}\, R_{Main}}{(\Omega R)_{Main}\, l_{Tail}} v_{i_{Tail}} \tag{2.2.23}$$

2.2.3 Forward Flight

In forward flight the flow-conditions starts to be really messy, mainly because the local airspeed depends on where you look at the rotor. To be able to analyze this, the Azimuth angle, ψ, is introduced. The Azimuth angle is zero over the tail-boom and is defined positive in the rotational direction. This will be discussed more in Section 2.3 and for now the flow is assumed to be evenly distributed. Another angle introduced is the angle of attack of the rotor disc, α_{TPP}. An estimation of α_{TPP} is:

$$\alpha_{TPP} = -tan^{-1}\left(\frac{D}{G.W.}\right) \tag{2.2.24}$$

Where α_{TPP} is defined positive when the nose pitches up.

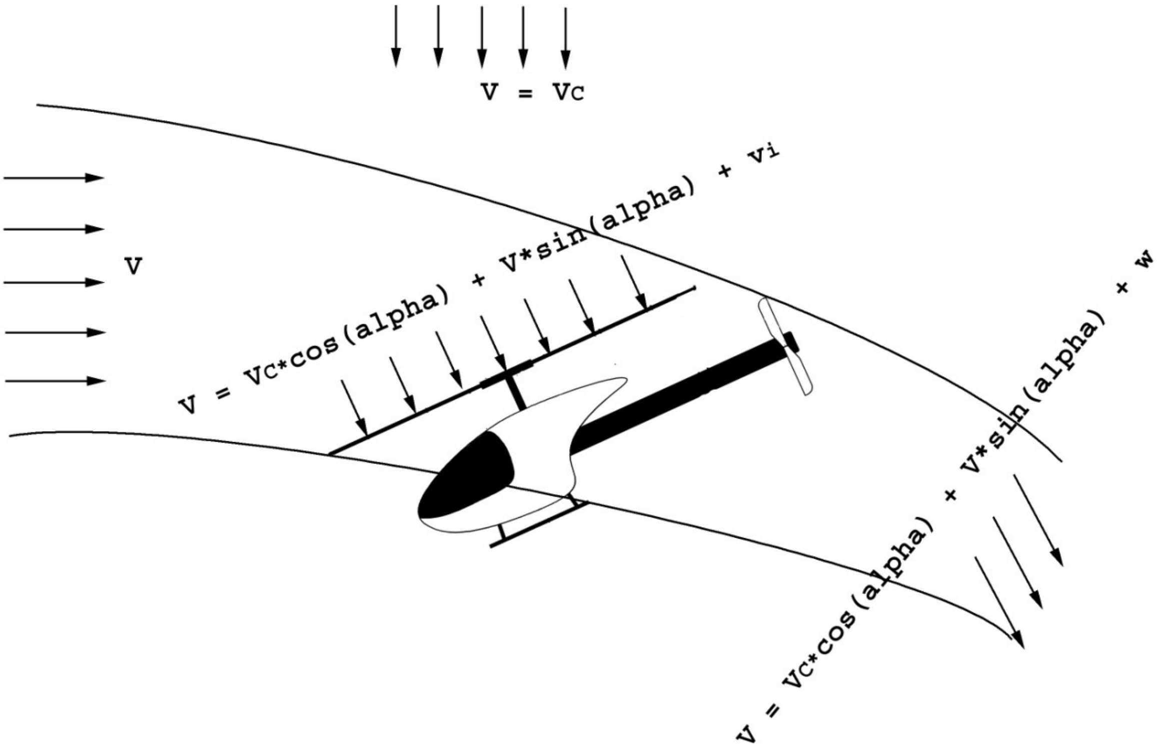


Figure 2-7. The mass flow thru the rotor in forward flight

The net mass flow thru the rotor disc is:

$$\dot{m}_1 = \rho A U \tag{2.2.25}$$

Where U is the resultant velocity at the disk. For high forward speeds it may be assumed that $U = V$ or the total velocity is equal to the forward velocity. Since thrust is defined the same way as in hover the thrust can be written:

$$T = 2\rho A V v_i \tag{2.2.26}$$

This high speed assumption is based on the assumption that $V \gg v_i$, this however is not a good assumption for small UAV helicopters because they are not flying as fast as bigger helicopters but the induced velocity is basically the same. Also in Eq 2.2.26 a small angle assumption regarding α_{TPP} has been made. In order to express the mass flow in a more correct way the components of the forward speed, climb speed, and induced speed needs to be accounted for. The resulting velocity at the disc can be expressed as:

$$U = \sqrt{\left(v_i + V_c \cos\alpha_{tpp} + V \sin\alpha_{tpp}\right)^2 + \left(V_c \sin\alpha_{tpp} + V \cos\alpha_{tpp}\right)^2} \tag{2.2.27}$$

The total mass flow thru the rotor disc is then:

$$\dot{m}_1 = \rho A \sqrt{(v_i + V_c \cos\alpha_{tpp} + V \sin\alpha_{tpp})^2 + \left(V_c \sin\alpha_{tpp} + V \cos\alpha_{tpp}\right)^2} \tag{2.2.28}$$

, the thrust is:

$$T = 2\rho A v_i \sqrt{(v_i + V_c \cos\alpha_{tpp} + V \sin\alpha_{tpp})^2 + \left(V_c \sin\alpha_{tpp} + V \cos\alpha_{tpp}\right)^2} \tag{2.2.29}$$

From Eq 2.2.29 the induced velocity can be calculated numerically and the thrust can be found from Eq 2.2.11. Note that if the forward speed and the disc angle of attack is set to zero the equation becomes:

$$T = 2\rho A(v_i + V_C)v_i \tag{2.2.30}$$

, that is the thrust equation in vertical climb. Likewise if the climb velocity is set to zero the trust equation from hover is obtained.

In forward flight another useful parameter called the *tip speed ratio* is often introduced. The tip speed ratio is the ratio between the inflow velocity parallel to the tip of the rotor and the rotational tip speed of the blades, it is defined by:

$$\mu = \frac{V \cos\alpha_{tpp} + V_c \sin\alpha_{tpp}}{\Omega R} \tag{2.2.31}$$

Since the rotor wake is not going straight down in forward flight experiments have shown that the induced velocity is different around the rotor disc, Leishman [2] p.159, and therefore the local induced velocity is introduced as.

$$v_L = v_i\left(1 + K\frac{r}{R}\cos\psi\right) \tag{2.2.32}$$

Induced Power

The induced power of the rotor occurs because of the induced velocities. To be able to estimate the induced power it is convenient to use the induced angle of attack defined as:

$$\alpha_{ind} = \frac{v_i}{V\cos\alpha_{tpp} + V_C\sin\alpha_{tpp}} \tag{2.2.33}$$

The induced drag can now be written as:

$$D_{ind} = T\sin\alpha_{ind} \tag{2.2.34}$$

, the induced power as:

$$P_{ind} = D_{ind}\left(V\cos\alpha_{tpp} + V_c\sin\alpha_{tpp}\right) \tag{2.2.35}$$

It can be seen in Eq 2.2.33 that if the forward speed is increased the induced angle of attack is decreased, this means that if the forward speed increases with a constant thrust the induced power decreases.

Parasite Power

The parasite power is the power required to overcome the drag from all of the helicopter's components except the rotors. By using Eq 2.2.10 the parasite drag can be written:

$$D_p = C_d S\frac{\rho}{2}\left(V\cos\alpha_{tpp} + V_c\sin\alpha_{tpp}\right)^2 \tag{2.2.36}$$

The parasite power-losses can then be described as:

$$P_p = D_p\left(V\cos\alpha_{tpp} + V_c\sin\alpha_{tpp}\right) \tag{2.2.37}$$

Profile Power

Profile power losses occur because of the friction of the air against the blades of the helicopter. The profile power coefficients can be estimated by:

$$C_Q/\sigma_0 = \frac{C_d}{8}(1 + \mu^2) \tag{2.2.38}$$

$$C_H/\sigma_0 = \frac{C_d\mu}{4} \tag{2.2.39}$$

Where Q is profile torque and H is the drag force in x-direction. C_d is the profile drag and is a function of the angle of attack and of the Reynolds's number. The total profile power required can now be described as:

$$P_0 = \left(C_Q/\sigma_0\right)\rho\sigma A(\Omega R)^3 + (C_H/\sigma_0)\rho\sigma A(\Omega R)^2\left(V\cos\alpha_{tpp} + V_c\sin\alpha_{tpp}\right) \tag{2.2.40}$$

The total power required is then:

$$P_{tot} = P_i + P_p + P_v + P_0 + P_{tail} \tag{2.2.41}$$

2.3 Blade Element Method

The Blade Element Method is a more advanced method for calculating the rotor performance than the momentum method. The basic idea is that the blade is divided into several elements and that the lift for each element can be calculated. In the momentum theory the flow over the rotor was assumed to be constant and equally distributed, in the blade element theory however the assumptions will be reduced to a minimum. As mentioned before the Azimuth angle, ψ, is introduced and the velocities will now be a function of the Azimuth angle. Another interesting phenomenon is blade flapping. Blade flapping occurs because of the differences in inflow velocity on the blade at different positions at the rotor, this phenomena is discussed more in Section 2.3.1. Since the blade is divided into elements it is convenient to introduce the distance to the local element, r.

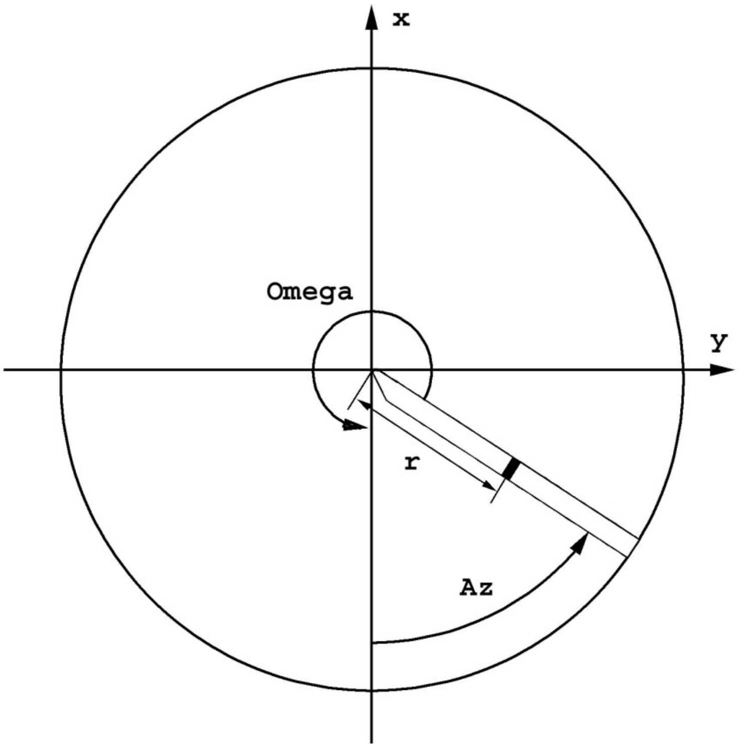


Figure 2-8. Rotor disc

The local velocity tangential to the blade can then be defined as:

$$U_T = \Omega r + V \sin\psi \tag{2.3.1}$$

Or if the tip speed ratio is being used:

$$U_T = \Omega R \left(\frac{r}{R} + \mu \sin\psi\right) \tag{2.3.2}$$

The perpendicular velocity is not as simple as the tangential one. In the perpendicular case terms like induced velocity, climb velocity and flapping velocities will occur. The perpendicular velocity is defined as:

$$U_P = V \sin\alpha_{tpp} - v_L - r\dot{\beta} - V\beta\cos\psi - V_C \cos\alpha_{tpp} \tag{2.3.3}$$

The velocities can be nondimensionalized by dividing them by ΩR. The total blade velocity can then be written as:

$$U_B = \sqrt{U_T^2 + U_P^2} \tag{2.3.4}$$

The total radial velocity is:

$$U_R = \mu \cos \psi \tag{2.3.5}$$

The local pitch angle around the blade is a function of the collective pitch, the blade twist and the cyclic pitch. The local pitch angle can be described as:

$$\theta = \theta_0 + \frac{r}{R}\theta_1 - A_1 \cos \psi - B_1 \sin \psi \tag{2.3.6}$$

Where A_1 and B_1 are the longitudinal and the lateral cyclic pitch required to keep the helicopter in trim. When the local pitch and the local velocities have been derived the local angle of attack of the airfoil can be described as:

$$\alpha = \theta + \tan^{-1} \frac{U_P}{U_T} \tag{2.3.7}$$

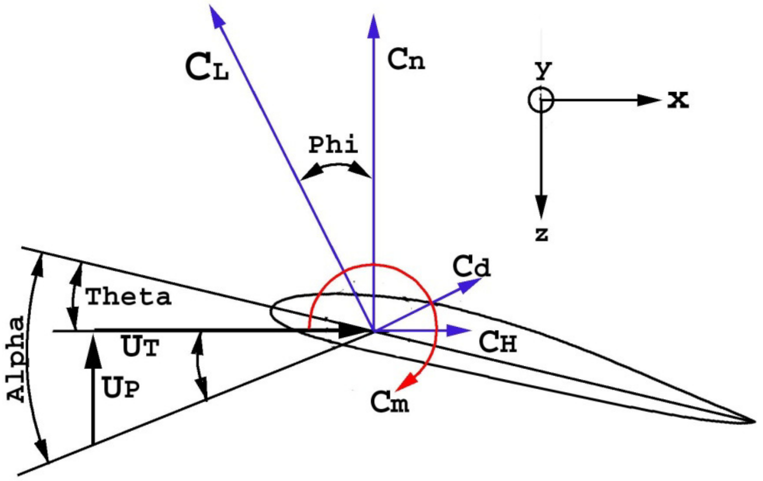


Figure 2-9. Local angle of attack

When the local angle of attack has been calculated the local lift and drag coefficients, C_L and C_D, can be estimated by use of some appropriate method. Once the lift and drag coefficients have been determined the normal force coefficient can be calculated as:

$$c_N = C_L \frac{U_T}{U_B} + C_D \frac{U_P}{U_B} \tag{2.3.8}$$

The total chordwise force consists of one profile force and one induced force. The profile force is a function of both the skin friction and the profile drag. The skin friction coefficient is estimated to be:

$$c_f = 0.006 \tag{2.3.9}$$

The profile drag coefficient is then:

$$c_{d_p} = c_d - c_f = c_d - 0.006 \tag{2.3.10}$$

The total chordwise “zero” drag coefficient is:

$$c_{c_0} = c_{d_p}\frac{U_T}{U_B} + c_f\frac{U_T\sqrt{U_T^2 + U_R^2}}{U_B^2} \tag{2.3.11}$$

The induced chordwise drag coefficient is:

$$c_{c_{ind}} = -c_l\frac{U_P}{U_B} \tag{2.3.12}$$

, the total chordwise drag force coefficient is:

$$c_c = c_{c_0} + c_{c_{ind}} \tag{2.3.13}$$

The pressure drag and the induced drag will only produce chordwise forces, but the skin friction however will produce a spanwise force as well. It can be expressed as:

$$c_s = c_f\frac{U_R\sqrt{U_T^2 + U_R^2}}{U_B^2} \tag{2.3.14}$$

The nondimensionalized thrust loading along the blade can then be described as:

$$\frac{dC_T/\sigma}{dr/R} = \frac{U_B^2}{2}c_N \tag{2.3.15}$$

, for the entire blade:

$$\Delta C_T/\sigma = \int_{x_0}^{B}\frac{dC_T/\sigma}{dr/r}dr/R \tag{2.3.16}$$

Where x_0 and B are tip loss factors. The total thrust of the rotor is the average thrust of a number of equally spaced Azimuth positions along the rotor:

$$C_T/\sigma = \frac{1}{N}\sum_{n=1}^{N}\Delta C_T/\sigma_n \tag{2.3.17}$$

From the normal force coefficient the pitching and rolling moment coefficient loadings can be calculated as:

$$\frac{dCM_{yM}/\sigma}{dr/R} = -\frac{U_B^2}{2}\frac{r}{R}\cos\psi\, c_N \tag{2.3.18}$$

$$\frac{dCM_{xM}/\sigma}{dr/R} = -\frac{U_B^2}{2}\frac{r}{R}\sin\psi\, c_N \tag{2.3.19}$$

, the total moments around the blade can be calculated the same way as the thrust. The contribution to the torque loading is:

$$\frac{dC_Q/\sigma}{dr/R} = -\frac{U_B^2}{2}\frac{r}{R}c_c \tag{2.3.20}$$

The force loading coefficient in x-direction can be calculated as:

$$\frac{dC_H/\sigma}{dr/R} = -\frac{U_B^2}{2}[c_c\sin\psi + c_s\cos\psi] \tag{2.3.21}$$

, the force loading coefficient in y-direction can be calculated as:

$$\frac{dC_Y/\sigma}{dr/R} = -\frac{U_B^2}{2}[-c_c\cos\psi + c_s\sin\psi] \tag{2.3.22}$$

Now all the forces and torques can be calculated and an equilibrium state for the helicopter can be established.

2.3.1 Flapping

Due to the velocity change around the rotor the advancing blade will tend to accelerate upward and the retreating blade will tend to accelerate downward. Because of this the rotor blades will not move in a strictly circular path around the helicopter but they will bend upwards and downwards in a harmonic movement. That motion can be expressed by a local flapping angle,β, defined like this:

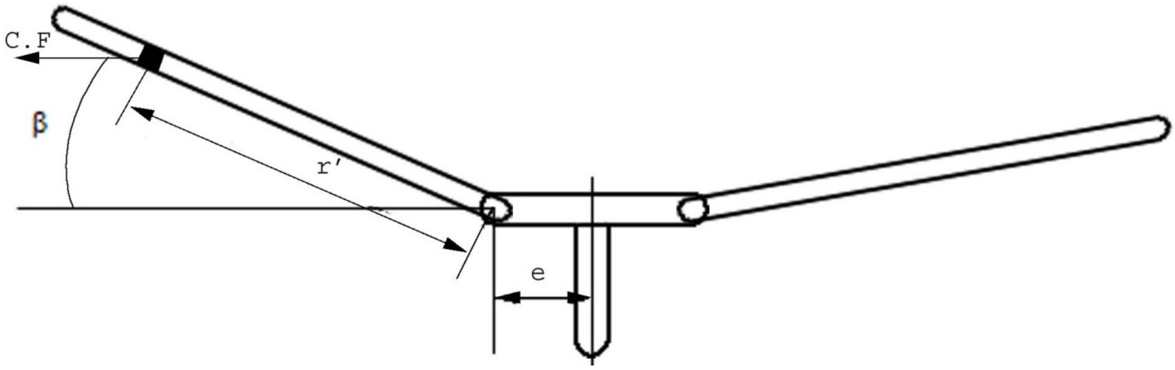


Figure 2-10. Blade flapping

The flapping motion can then be expressed by an infinite Fourier series like

$$\beta = a_0 - a_{1_s} \cos\psi - b_{1_s} \sin\psi - \ldots - a_{n_s} \cos\psi - b_{n_s} \sin\psi \tag{2.3.23}$$

If all higher terms of harmonics are assumed to be zero the motion can be described as:

$$\beta = a_0 - a_{1_s} \cos\psi - b_{1_s} \sin\psi \tag{2.3.24}$$

Because of the flapping the two terms $r\dot{\beta}$ and $V\beta\cos\psi$ appears in Eq 2.3.3. The first term, $r\dot{\beta}$, appears because of the flapping angular velocity and the second term, $V\beta\cos\psi$, appears because of the component of the forward velocity that contributed to the perpendicular flow.

In Eq 2.3.23 a_0 represents the coning of the blades, a_{1_s} represents the longitudinal flapping and b_{1_s} represents the lateral flapping. To obtain these trim parameters an equilibrium state will have to be found. The blades will be in equilibrium when the centrifugal, aerodynamical and weight forces and moments are trimmed to zero, i.e.:

$$M_{C.F} + M_A + M_W = 0 \tag{2.3.25}$$

The centrifugal moment around the flapping hinge for a blade element is:

$$dM_{C.F} = -mr'(r' + e)\Omega^2 \left[a_0 - \frac{e}{r'+e}\left(a_{1_s} \cos\psi + b_{1_s} \sin\psi\right)\right] dr \tag{2.3.26}$$

and for the entire blade:

$$M_{C.F} = \int_0^{R-e} dM_{C.F} = -\Omega^2 \left\{a_0 \left(I_b + e\frac{M_b}{g}\right) - \left(a_{1_s} \cos\psi + b_{1_s} \sin\psi\right) e\frac{M_b}{g}\right\} \tag{2.3.27}$$

The moment contribution due to weight is:

$$M_W = -M_b = -\int_0^{R-e} mgr'dr' = -\frac{mgR^2}{g}\left(1-\frac{e}{R}\right)^2 \tag{2.3.28}$$

The aerodynamic moment for a blade element is:

$$dM_A = r'\frac{\rho}{2}U_T^2 a\alpha c dr' \tag{2.3.29}$$

Where U_T and α are defined in Eq 2.3.2 and 2.3.7. However if a hinge offset is being used the tangential velocity may be written as:

$$U_T = \Omega R\left(\frac{r'+e}{R} + \mu \sin\psi\right) \tag{2.3.30}$$

When the aerodynamic moment has been calculated it is convenient to do the same approximation as for the flapping angle, that all the higher harmonics are zero. To be able to find the flapping parameters it is necessary to divide the moments into one constant term, one sine term and one cosine term, like:

$$M_W = M_{W_{const}} \tag{2.3.31}$$

$$M_{C.F} = M_{C.F_{const}} + M_{C.F_{sine}} \sin\psi + M_{C.F_{cosine}} \cos\psi \tag{2.3.32}$$

$$M_A = M_{A_{const}} + M_{A_{sine}} \sin\psi + M_{A_{cosine}} \cos\psi \tag{2.3.33}$$

The constant term will then give the coning, the sine term will give the lateral flapping and the cosine term will give the longitudinal flapping. The flapping constants can be calculated by stating:

$$M_{A_{const}} + M_{C.F_{const}} + M_W = 0 \tag{2.3.34}$$

$$M_{C.F\,cosine} + M_{A_{cosine}} = 0 \tag{2.3.35}$$

$$M_{C.F\,sine} + M_{A_{sine}} = 0 \tag{2.3.36}$$

Solving Eq 2.3.34 for a_0 gives, Prouty [3] chapter seven:

$$a_0 = \frac{\frac{2}{3}\gamma C_T/\sigma}{a}\left[\frac{\left(1-\frac{e}{R}\right)^2}{1+\frac{e}{2R}}\right] - \frac{\frac{3}{2}gR}{(\Omega R)^2}\left[\frac{1}{1+\frac{e}{2R}}\right] \tag{2.3.37}$$

Eq 2.3.35 and 2.3.36 gives, Prouty [3] chapter seven:

$$\Omega^2 b_{1_s} e \frac{M_b}{g} + \frac{\gamma I_b}{2} \Omega^2 \left(1 - \frac{e}{R}\right) \left[\frac{2}{3}\theta_0 \mu + \frac{1}{2}\theta_1 \mu - B_1 \left(\frac{1}{4} + \frac{3}{8}\mu^2\right) + \frac{\mu}{2}\left(\mu \alpha_s - \frac{v_i}{\Omega R}\right) - a_{1_s}\left(\frac{1}{4} - \frac{\mu^2}{8}\right)\right] = 0 \qquad (2.3.38)$$

$$\Omega^2 a_{1_s} e \frac{M_b}{g} + \frac{\gamma I_b}{2} \Omega^2 \left(1 - \frac{e}{R}\right) \left[-A_1 \left(\frac{1}{4} + \frac{\mu^2}{8}\right) - \frac{\mu a_0}{3} - \frac{K v_i}{3\Omega R} + b_{1_s}\left(\frac{1}{4} - \frac{\mu^2}{8}\right)\right] = 0 \qquad (2.3.39)$$

This equation system can be solved numerically for a_{1_s} and b_{1_s} by writing them on matrix form like:

$$\begin{bmatrix} -\frac{\gamma I_b \Omega^2}{2}\left(1 - \frac{e}{R}\right)^2 \left(\frac{1}{4} - \frac{\mu^2}{8}\right) & \frac{\Omega^2 e M_b}{g} \\ \frac{\Omega^2 e M_b}{g} & \frac{\gamma I_b \Omega^2}{2}\left(1 - \frac{e}{R}\right)^2 \left(\frac{1}{4} + \frac{\mu^2}{8}\right) \end{bmatrix} \begin{pmatrix} a_{1_s} \\ b_{1_s} \end{pmatrix} =$$

$$\begin{bmatrix} -\frac{\gamma I_b \Omega^2}{2}\left(1 - \frac{e}{R}\right)^2 \left(\frac{2}{3}\theta_0 \mu + \frac{1}{2}\theta_1 \mu - B_1\left(\frac{1}{4} + \frac{3}{8}\mu^2\right) + \frac{\mu}{2}\left(\mu \alpha_s - \frac{v_i}{\Omega R}\right)\right) \\ -\frac{\gamma I_b \Omega^2}{2}\left(1 - \frac{e}{R}\right)^2 \left(-A_1\left(\frac{1}{4} + \frac{\mu^2}{8}\right) - \frac{\mu a_0}{3} - \frac{K v_i}{3\Omega R}\right) \end{bmatrix} \qquad (2.3.40)$$

Now all of the flapping parameters can be calculated and be used as input to the pitch and to the angle of attack equations.

3rd Chapter

Conceptual Design Process

When starting the design of a new helicopter the first step is to define the goals of the design. The goals of the design can be mission requirements, performance requirements and/or cost goals. Mission requirements can be payload capacity, endurance, range, speeds and physical size. Performance requirements can in many cases be the same as mission requirements but also other things not necessarily dictated by the mission. In some cases it can be requirements on climb speed, service ceiling, autorotative landing capability, one-engine-out performance etc. In many cases there are also goals to cut operational cost of a new design compared to older helicopters. All of these specifications must be considered in the design work and they are all going to govern how the final design of the helicopter will be.

A major part in conceptual design is statistics from previous designs. By comparing the goals of the new helicopter with statistics, relations can be found to predict sizing parameters for the new helicopter. Typical first estimations based on statistics can be MTOW, main rotor diameter and installed engine power. The statistics can also be used to predict weights of different part of the helicopter such as chassis, rotor blades, gearbox etc. Naturally more data from other helicopters means that the prediction for the new helicopter will be better. The predictions could also include the influence of new technology to the design regarding performance and weights.

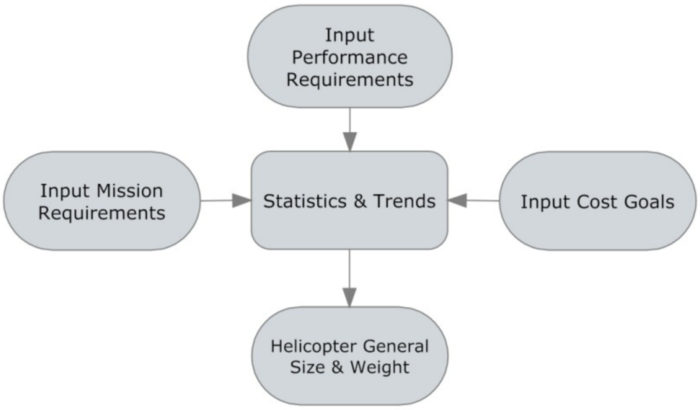


Figure 3-1. Flowchart of the first stage in conceptual design process

After using the statistics to get a first estimation of the helicopters sizing, such as MTOW, main rotor diameter and engine power, more details are applied to the design. In the more detailed design things like rotor blade chord, rotor blade twist, blade tip Mach number and more are specified. In some cases in the later stages of conceptual design predictions are not used to estimate weight and performance of engine, electronics and other systems. Instead COTS components are used. Based on the more detailed geometrical sizing of the helicopter the weight of the different components such as chassis and rotor blades can be predicted with increased accuracy.

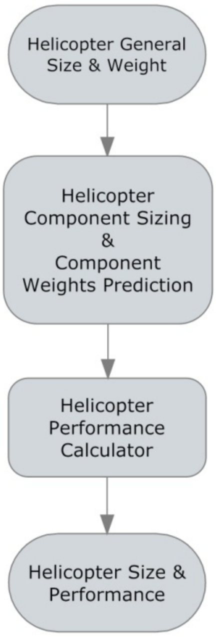


Figure 3-2. Flowchart of the last stage in conceptual design process

When the overall helicopter design has been established it is used as input together with the design goals to predict performance of the helicopter. The performance calculations are based on the theories described in chapter two and will give the engineer a good estimation of the performance and if the helicopter is able to fulfill the different requirements.

Since the tools and methods used during the conceptual design process are quite simple and not so time consuming the designer has a good opportunity to test and evaluate many different configurations. Optimization algorithms can often be used to further improve and speed up the search for the best design.

4th Chapter
Design Tool Layout

To start the design work on the Conceptual Design Tool a number of different key features and requirements were put up for the program. The requirements were:

- Graphical user interface
- Upgradeable with new functions in the future
- Be able to communicate with other softwares

The programming language to be used in the development of the Design Tool was desired to be open source and to have a programming syntax know to the authors.

From the beginning the idea was to create the graphical user interface in Microsoft Excel and do the computational part of the program in Mathworks Matlab with a link between the two programs. The main reason was Microsoft Excel's good capability to communicate with other softwares and Mathworks Matlab's good upgradeability with different toolboxes. Both of these programs are also well known by the authors. Unfortunately these programs cost quite a lot of money and since the contractor CybAero wants to be cost effective other solutions had to be investigated.

The solution was to use the open source program Scilab version 4.1.2 [8] that is a numerical computation programming language released under the GNU GPL [9] license agreements. Besides numerical computation Scilab can be used to create graphical user interfaces and it utilizes a programming syntax much like the one used by Mathworks Matlab. Scilab can be connected to other softwares and there are a growing number of toolboxes available.

Considering the given time frame for the thesis work some restrictions had to be made to which parts of the conceptual design process to be incorporated into the Design Tool. The parts finally incorporated into the Design Tool were:

- Basic mission requirements
- Ground transport requirements
- General sizing based on statistical trends
- COTS engine selection
- Main and tail rotor detail design
- COTS systems selection
- Weight predictions based on statistical trends
- Performance calculations based on blade element theory

For the basic mission requirements a simplified model of two real missions is used which lets the user set desired requirements like payload weight capacity, speed for endurance flight, endurance time, speed for range flight, range, mission altitude and more. For the ground transport requirements the user can set desired dimensions of the transport space and maximum allowed weight for the helicopter.

The flowchart in Figure 4-1 shows how the Conceptual Design Tool is built up, describing in general how the tool is working. The rest of this chapter is devoted to describe in more detail how the different modules of the program are working.

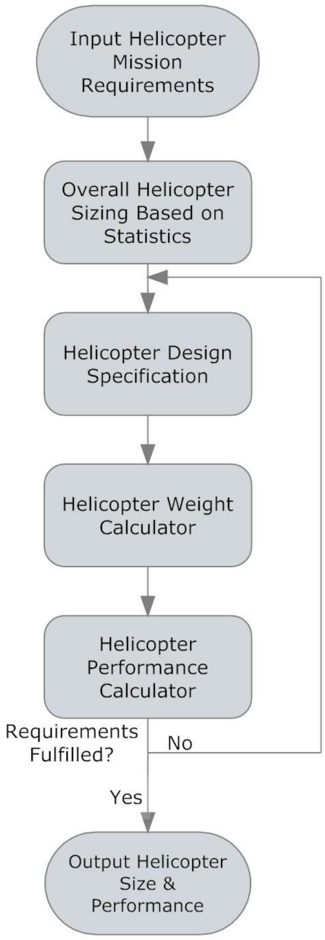


Figure 4-1. Flowchart of main program

4.1 Statistical Database

By studying data from different VTOL UAVs patterns can be seen on how payload weight, MTOW, main rotor diameter and installed engine power relates to each other. This can be used in the design work to get a first rough estimation on the general size of the helicopter regarding MTOW, main rotor diameter and installed engine power. This will give the designer a good starting point for the rest of the design work.

Since the data in the database are collected from manufacturers some caution must be taken into account because of the uncertainty that the values specified by the manufacturers really corresponds to actual performance data and not just “sales” data.

The database is very crudely built up around an excel-sheet where each column corresponds to a helicopter with the basic data filled in on each row. When the Conceptual Design Tool is started Scilab automatically imports the data in the excel-sheet with the built in Scilab command “xls_read”. In the Conceptual Design Tool the user can select different sets of data to plot in a diagram and also the style of an approximation curve to the data. The user can plot MTOW versus payload weight, engine power versus payload weight, engine power versus MTOW and main rotor diameter versus MTOW. The statistical trend of the data can be approximated by five curve styles; linear, exponential, logarithmic, quadratic and cubic depending on which one the user thinks fit the data best.

4.2 Engine

4.2.1 Engines on the Market

There are a number of engines available on the market that are suitable to be used for VTOL UAVs in the specified weight range aimed for with this Conceptual Design Tool. Data on these engines are collected and put into a database for the Conceptual Design Tool to use in the design process. The data that is put into the database consists of general information on the engine such as manufacturer, fuel system, engine type, fuel type, cooling system, time between overhaul etc. Engine characteristics like power versus rpm, torque versus rpm and specific fuel consumption versus rpm are also saved into the database.

4.2.2 Compensation for Altitude

As altitude is increased the available power from the engine is decreased due to the thinner air. The change of engine power is proportional to the change of air density compared to ISA reference density. Using the equations below gives a good estimation on available engine power at a certain altitude and temperature, however Eq 4.2.3 does not give a good approximation for supercharged engines.

$$p = p_{ref}\left(\frac{(T-H\,L)}{T}\right)^{\frac{g}{L\,R}} \tag{4.2.1}$$

$$\rho = \frac{p}{\left(R(T-H\,L)\right)} \tag{4.2.2}$$

$$P = P_{ISA}\left(\frac{\rho}{\rho_{ISA}}\right) \tag{4.2.3}$$

4.3 Airfoil Performance Data

Rotor performance is largely dependent on airfoil selection so it is important to evaluate many different airfoils for the rotor blades to get good helicopter performance. Hence it is desired to have a large database of different airfoils and their characteristics. Unfortunately airfoil performance data is hard to get hold of from experiments and the environmental parameters under which the tests were conducted varies a lot. This makes it hard to compare results from different airfoils and tests. There are a number of different computer programs available that can be used to generate airfoil performance data so that the data is easy to use and compare. To meet the requirements for this project such a program is desired to perform the calculations fast, give reliable results and be free to use. Among the many programs available XFOIL version 6.94 [10] was chosen to build up the database due to its high speed calculation of airfoil data and generally good results which have been validated in different studies like "Design of Airfoils for Wind Turbines Blades" [5] by V. Parenzanovic, B. Rasuo and M. Adzic.

Considering the helicopter size range for which the Conceptual Design Tool is aimed for it was assumed to be adequate to only study airfoil performance for Reynolds's numbers from 50 000 up to 5 000 000 and angles of attack between -10° and 15°. The calculations are stepped forward with step size 200 000 for Reynolds's numbers and 0.2° for angles of attack. Values in between can easily be interpolated with only a small loss of accuracy.

The connection between XFOIL and Scilab was first done by letting Scilab create a VBScript file containing information for XFOIL about which airfoil, Reynolds's numbers and angles of attack the calculations should be performed. The Scilab command "winopen" then executed a Windows batch file which opened XFOIL and ran the instructions in the VBScript file previously created by Scilab. XFOIL saved the results from the calculations in a text file that was read into Scilab and the airfoil specific results were saved into an airfoil performance database. The drawback was that the connection only worked under Windows. Instead the command "host" was utilized which works both under Windows and Linux. The command directly writes instructions in Windows command prompt or the Linux terminal and an instruction script can be saved in an ordinary text file so that the VBScript file is not needed.

4.4 Rotor Design

The rotor blades are one of the most important parts of the helicopter regarding the helicopters performance and the shape of the rotor blades can be very complex. Many helicopters in service today have a variety of different airfoils at different locations on the rotor blade and the geometrical shape of the blade tip can be very advanced like the BERP blade tip seen in Figure 4-2.

Figure 4-2. Close-up view of a BERP rotor blade tip

The blades are also often twisted with a linear change of the blade pitch along the span, where the inner section of the blade is at a larger angle of attack than the outer sections. More details on advanced rotor blade design can be found in Prouty [3] and Leishman [2].

During the conceptual design phase of a new helicopter there are usually limitations in how complex the rotor blade geometries can be made in order for the tools at hand to give valid results. The uncertainty on how well the theoretical helicopter model could deal with different airfoils at different positions on the rotor blade lead to a restriction in the program to only allow one airfoil along the whole span. The allowed design of the rotor blade tip was restricted for the same reason.

In the Conceptual Design Tool the design parameters for the main rotor are:

- Main rotor diameter
- Rotor blade chord
- Number of rotor blades
- Rotor blade linear twist
- Rotor blade tip taper ratio
- Rotor blade tip start
- Rotor blade tip Mach number for hover conditions

The main rotor is without a Bell-Hiller stability system [11]. For VTOL UAVs the use of a Bell-Hiller system is not needed because of the flight control unit.

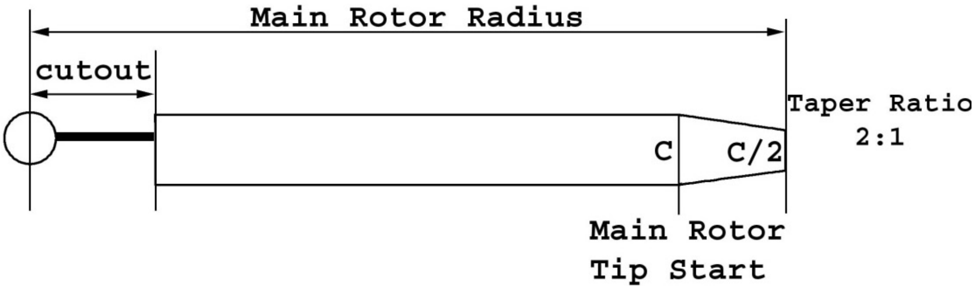


Figure 4-3. Sketch of rotor blade

The cutout closest to the rotor hub is set to be either 15% of the rotor blade radius or where the Reynolds's numbers on the blade are smaller than 50 000, depending on which gives the biggest cutout of the two.

The design parameters for the tail rotor are:

- Tail rotor diameter
- Rotor blade chord
- Number of rotor blades
- Rotor blade tip taper ratio
- Rotor blade tip start
- Rotor blade tip Mach number for hover conditions
- Tail boom length

In the Design Tool the tail rotor is modeled as a so called tractor and the blades do not have any linear twist. The linear twist is skipped as a design parameter since it is not likely that there will be a linear twist on the tail considering the aimed helicopter size range for the Design Tool. Also the change in needed total power for the helicopter is very small whether the tail has linear twist or not. By the parameter tail boom length it is meant the distance between main rotor shaft and tail rotor shaft and not the actual length of any component on the helicopter called tail boom. More details on tail rotor design can be found in Prouty [3] and Leishman [2].

4.5 Helicopter Electronic Systems

The electronic systems on the helicopter are electronic components vital for the helicopter to fly. The components that can be selected in the Conceptual Design Tool are flight control units, command links, servo actuators, batteries and generators. All components that can be selected are actual components available on the market.

Since CybAero already has a database over different electronics for VTOL UAV helicopters a connection between Scilab and the MySQL [12] database was created. The connection was made in a similar way as the connection to XFOIL. Scilab instructs the MySQL command line client directly by the command "host". The information in the database can be retrieved and saved locally in text files when the user clicks on a button in the Design Tool. In this way it is possible to work offline without a connection to the database and use the recently downloaded version of the information from the database.

4.6 Weight Estimations

To estimate OEW and MTOW for the helicopter a series of calculations are made based on assumptions and statistics from other helicopters. The weight calculations are performed iteratively until the change of MTOW between each step is less than 1%. The weight calculations for the helicopter are performed according to the scheme in Figure 4-4.

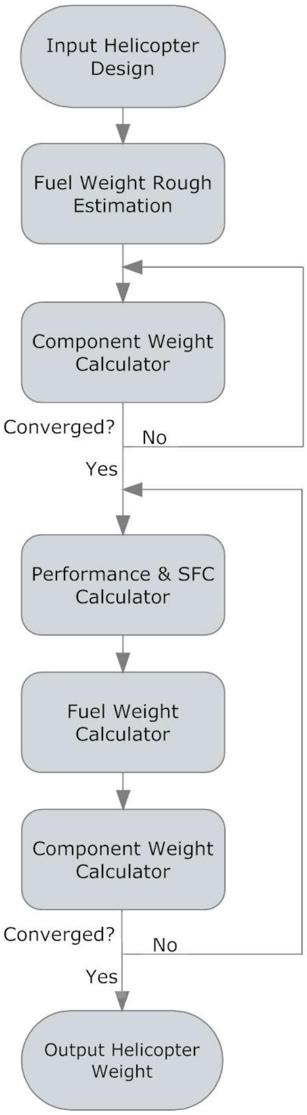


Figure 4-4. Flowchart for weight calculations

4.6.1 Fuselage

The fuselage is divided into four sub components consisting of chassis, hull, tail boom and landing skids. Chassis is the load carrying structure or frame inside of the helicopter. It is assumed that it varies linearly to MTOW of the helicopter. Hull is the outer shell of the helicopter and the weight of it is assumed to be proportional to the volume inside of the hull. To make the calculations easier and the design work simpler the shape of the hull is predefined as elliptical with the major axis set to a ratio of the main rotor radius and the minor axis set to a ratio of the major axis. The tail boom is treated in the same way as the hull and said to be proportional to the volume contained within the tail boom. The tail boom is set to be a cylinder with a predefined ratio between length and diameter. Since the landing skids are load carrying in the same way as the chassis it is dealt with in the same way and said to be proportional to MTOW. K_i are constants empirically derived from statistics from other helicopters.

$$m_{Chassis} = K_{Chassis} \cdot MTOW \qquad (4.6.1)$$

$$m_{Hull} = K_{Hull} \cdot V_{Hull} \qquad (4.6.2)$$

$$m_{Tail\ Boom} = K_{Tail\ Boom} \cdot V_{Tail\ Boom} \qquad (4.6.3)$$

$$m_{Landing\ Skids} = K_{Landing\ Skids} \cdot MTOW \qquad (4.6.4)$$

4.6.2 Main Rotor

The weight of the main rotor consists of the weight of the rotor blades and the weight of the hub and shaft (No Bell-Hiller system). At the first stage the individual weight of a rotor blade is calculated. To make calculations easier the blade cross-section is assumed to be elliptical so that the cross-sectional area can be easily calculated. Using this approximation the volume of the blade is calculated and multiplied with an empirically derived density of the blade. To estimate the weight of the shaft and hub the rotational energy is used. The rotational energy consists of moment of inertia for all blades and the rotational speed of the blades. The rotational energy is then multiplied with a constant in order to get the estimated weight of the rotor hub and shaft. It is also assumed that the rotor blades and the rotor hub can be manufactured in a more effective way as the size increases, giving room for more optimal solutions.

$$m_{Ind.Blade} = \left(\frac{K_{Size}}{V_{Ind.Blade}}\right)^{\frac{1}{5}} \cdot K_{Ind.Blade} \cdot V_{Ind.Blade} \qquad (4.6.5)$$

$$m_{Blades} = N_{Blades} \cdot m_{Ind.Blade} \qquad (4.6.6)$$

$$m_{Hub\ \&\ Shaft} = 0.995^{\left(\frac{I \cdot \omega^2}{K_{Rotation\ \ MR}} - 1\right)} \cdot \left(\frac{1}{K_{Rotation\ \ MR}} \cdot I \cdot \omega^2\right)^{\frac{1}{4}} \cdot K_{Hub\ MR} \qquad (4.6.7)$$

4.6.3 Tail Rotor

The tail rotor is treated the same way as the main rotor. The only difference is the additional weight of the transmission to the tail rotor. The weight of the transmission is set to be proportional to the length of the tail boom and the installed engine torque.

$$m_{Ind.Blade} = \left(\frac{K_{Size}}{V_{Ind.Blade}}\right)^{\frac{1}{5}} \cdot K_{Ind.Blade} \cdot V_{Ind.Blade} \tag{4.6.8}$$

$$m_{Blades} = N_{Blades} \cdot m_{Ind.Blade} \tag{4.6.9}$$

$$m_{Hub\ \&\ Shaft} = 0.995^{\left(\frac{I \cdot \omega^2}{K_{Rotation\ \ TR}} - 1\right)} \cdot \left(\frac{1}{K_{Rotation\ \ TR}} \cdot I \cdot \omega^2\right)^{\frac{1}{4}} \cdot K_{Hub\ TR} \tag{4.6.10}$$

$$m_{Transmission} = 0.995^{\left(\frac{M_{Engine}}{K_{Torque}} - 1\right)} \cdot K_{Transmission} \cdot L_{Tail\ Boom} \cdot \left(\frac{M_{Engine}}{K_{Torque}}\right)^{3/2} \tag{4.6.11}$$

4.6.4 Engine Components

The engines in the database are generally only specified as the engine alone, gearbox, oil and cooling system is not taken into account in the weight specified. Since the gearbox often is tailor made for a specific helicopter no database of gearboxes can in an easy way be built up, instead the weight has to be estimated. From the square-cube-law one can get the relationship below. The cooling system and engine oil weight is assumed to be proportional to the installed engine power. If the engine is a two-stroke engine no oil is included in the total engine weight and no weight is added for the cooling system if the engine is air cooled.

$$m_{Gearbox} = 0.995^{\left(\frac{M_{Engine}}{K_{Torque}} - 1\right)} \cdot K_{Gearbox} \cdot \left(\frac{M_{Engine}}{K_{Torque}}\right)^{3/2} \tag{4.6.12}$$

$$m_{Cooling\ sys.} = K_{Cooling\ sys.} \cdot P_{Engine} \tag{4.6.13}$$

$$m_{Engine\ oil} = K_{Engine\ oil} \cdot P_{Engine} \tag{4.6.14}$$

4.6.5 Fuel

Before the performance calculations for the helicopter can be performed the fuel is roughly estimated using two simple equations and selecting the highest calculated fuel weight of the two. It is assumed that the power for best endurance is around 40% of the max power and that there is a need for about 10% extra fuel in reserve. Power needed for range is assumed to be around 60% of maximum power.

$$m_{fuel} = max\left\{\begin{matrix} SFC_{mean} \cdot 0.4 \cdot P_{Engine\ max} \cdot t_{Endurance} \cdot 1.10 \\ SFC_{mean} \cdot 0.6 \cdot P_{Engine\ max} \cdot \left(\frac{Range}{V_{Range}}\right) \cdot 1.10 \end{matrix}\right\} \tag{4.6.15}$$

After the estimation for fuel weight has been performed along with the other weight estimations a first approximation for the helicopters OEW and MTOW is obtained.

Using these values the second more advanced stage of the helicopter weight estimation can be executed.

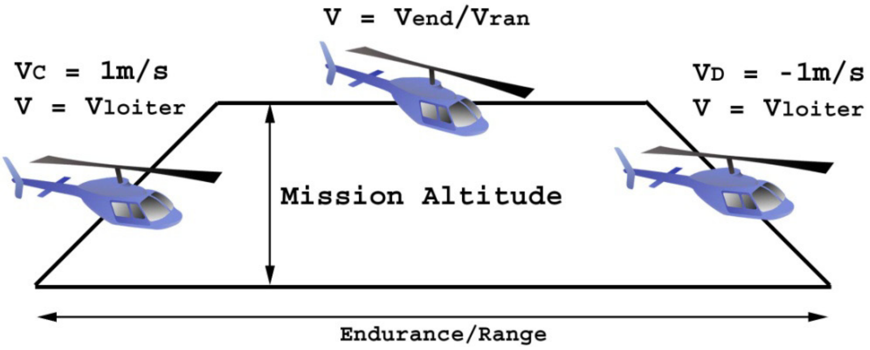


Figure 4-5. Typical mission appearance

The more advanced stage is started off with calculation of SFC. The SFC is selected by finding the rpm at which the ratio between engine power and SFC is the highest. If the engine is a two-stroke engine 2% extra is added to the SFC to compensate for the extra weight from two-stroke oil. The fuel calculator then separately simulates flying the endurance mission and then the range mission with the parameter settings specified as mission requirements. Range and endurance are defined as the distance and time from take-off to landing. Figure 4-5 shows a sketch of a mission. During the calculations the two equations seen below are used to calculate fuel weight for the endurance and the range mission.

$$m_{fuel} = SFC \cdot P_{Endurance} \cdot t_{Endurance} \tag{4.6.16}$$

$$m_{fuel} = SFC \cdot P_{Range} \cdot \left(\frac{Range}{V_{Range}}\right) \tag{4.6.17}$$

The missions start with warm up of the engine for five minutes where the engine is working at 25% of its capacity. The helicopter then climbs up to the specified mission altitude, flies the mission and descends down to the starting altitude. The fuel used for the different parts of the mission is summed up and as mentioned above 10% extra fuel is added as reserve fuel. For each part of the missions the calculator starts with an estimation of fuel needed for that part and then iterates until convergence has been reached to get the fuel used for that mission part. The mission requiring the most fuel will be dimensioning for the helicopter, giving a new OEW and MTOW. The fuel calculator iterates until MTOW and fuel weight does not change more than 1% each between the iterations.

4.7 Performance Calculations

In order to calculate the performance of a specific helicopter the theory in chapter two needs to be implemented in some way, in this case by use of a calculation program. The performance calculation program is an iterative program that iterates until an equilibrium state has been found for the helicopter. The data flow thru the program is described in Figure 4-6.

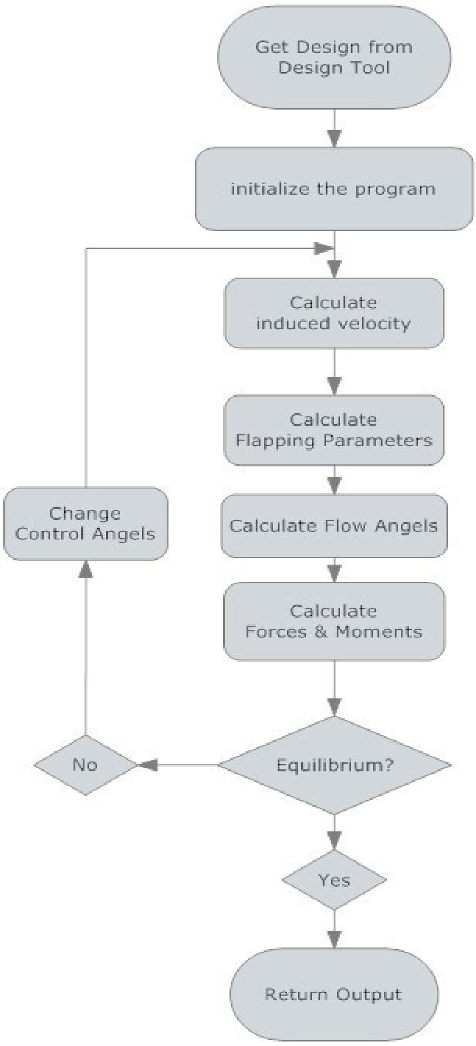


Figure 4-6. Flowchart of calculation program

In the initialization of the program the number of blade elements, Azimuth spacing and the maximum allowed iterations is pre-set to:

- n = 50
- Az = 15°
- Max_itt = 150

When initializing the program the collective pitch is set to twelve degrees plus the linear twist, all other control angles are set to zero degrees. That initialization is because collective pitch is always required in some amount but the rest of the control angles are not required for all flight cases. During one iteration the equations from chapter two and three are solved numerically and the forces and moments are obtained. When the forces and moments are known the equilibrium state for the helicopter can be established and the control angles can be corrected if the equilibrium is not satisfied. The convergence criteria for the forces and moments are that the nondimensionalized differences in force should be less than 0.0005 and the difference in moments in all direction should be less than 0.00005. For a 150kg VTOL UAV this normally corresponds to:

- $\Delta F = \pm 9.5N$
- $\Delta M = \pm 1.55Nm$

If the convergence criterion is not reached the control angles are changed by a scheme based on the nondimensionalized differences in each direction like:

$$\theta_0 = \theta_0 + K \cdot -C\Delta vertical \,/\, \sigma \tag{4.7.1}$$

$$\alpha_s = \alpha_s + K \cdot -C\Delta longitudinal \,/\, \sigma \tag{4.7.2}$$

$$\beta_s = \beta_s + K \cdot -C\Delta lateral \,/\, \sigma \tag{4.7.3}$$

$$A_1 = A_1 + K \cdot -C\Delta pitch \,/\, \sigma \tag{4.7.4}$$

$$B_1 = B_1 + K \cdot -C\Delta roll \,/\, \sigma \tag{4.7.5}$$

Where K is a constant determined by testing. The equilibrium in torque simply generates a tail rotor force that needs to be produced and indirectly the collective pitch required for the tail rotor. When the program converges the required power is returned to the user along with the required control angles.

4.7.1 Power versus Forward Speed

The aim of this solver is to estimate the required power to fly at a certain forward speed. The power versus forward speed predictor is a simple iterative program. It has a predetermined speed range with an unreachable maximum speed. The program simply iterates over the speed range and returns the required power for each speed and stops when the power required is higher than the engine power available. All performance calculations of power versus forward speed are done at the specified mission altitude.

4.7.2 Altitude versus Forward Speed

The goal of this solver is to find the service ceiling of the helicopter at different forward speeds. The service ceiling is defined as the upper altitude limit at which the helicopter can climb at 0.5m/s. The first version of the altitude versus forward speed solver iterated over the forward speed and for each forward speed it iterated over the altitude with a certain iteration length. This method was really slow and the accuracy was not great since the iteration step-length had to be large in order to keep the iteration time down.

Instead of that method a bisection method was used. The bisection method converges in a predefined number of iterations with a constant accuracy. The accuracy is about four times better than the method above and the calculation time is much smaller. One problem that may occur is that the actual altitude is higher than the maximum final value of the bisection method, this is best avoided by selecting a good start value.

4.7.3 Climb Speed versus Forward Speed

The climb speed versus forward speed solver uses exactly the same bisection method as in the altitude solver, the only difference is the staring value. All maximum climb speeds are calculated at mission altitude.

4.7.4 Payload versus Endurance

The aim of the payload versus endurance solver is to estimate the maximum endurance for a range of payloads at different altitudes. The basic assumption is that if payload weight is removed the empty space is filled with fuel. The helicopter weight is set to MTOW minus half the useable fuel weight (excluding the reserve fuel). When the power has been calculated and the SFC and fuel weight are known the endurance can be calculated for the specific case. The calculated endurance is calculated for the optimal endurance speed, which is obtained from the power versus forward speed calculator.

4.7.5 Payload versus Range

The goal of the range versus payload solver is to obtain the range for different payloads. The calculations are done in the same way as in the endurance versus payload solver except that the best speed for range is used instead of the best speed for endurance.

4.8 Results & Comparison Part of Program

In order to get a good overview of the helicopter the last section in the Conceptual Design Tool is devoted to be a summarization of the helicopter and its characteristics. All results from the performance calculation mentioned above can be plotted for easy viewing and comparison. A simple sketch of the helicopter is available both in top view and side view. In the sketch of the helicopter the transport requirements can also be seen as a frame around the helicopter along with a figure of a man that is 1.8m tall. This gives a good reference to the size of the helicopter and how well it fits into the required transport space.

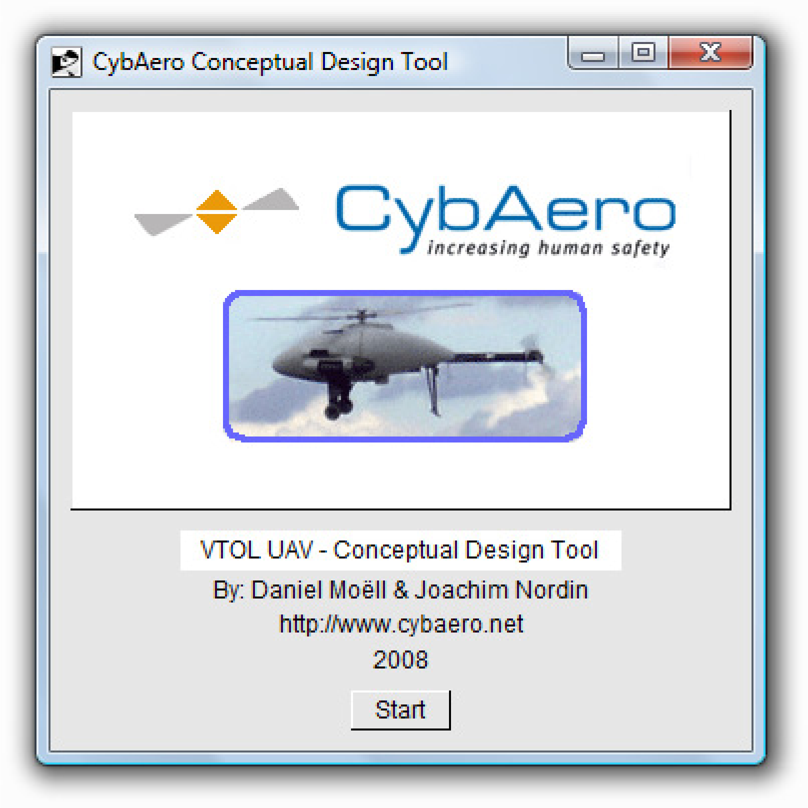
To estimate how the helicopters range and endurance varies with a specific payload a simple calculator is built in where it is possible to select payloads from a list. The list is connected to CybAero’s database over payload options in the same way as the helicopters electronic systems database is.

To compare the new helicopter design to other helicopters on the market four plots are available. In the plots MTOW versus payload, engine power versus payload, engine power versus MTOW and main rotor radius versus MTOW of the design can be viewed and compared to other helicopters.

5th Chapter
Results & Discussion

In this chapter the results will be displayed and discussed. The main result from this thesis is the Conceptual Design Tool and its functions. The results and discussion part will focus on the design and performance of the Design Tool, not on how the program is supposed to be used and not how different parameters affects the helicopter performance. The user's manual for the Design Tool can be found in Appendix. How the input to the Design Tool affects the helicopter performance is for the user to find out on his/her own.

5.1 Appearance



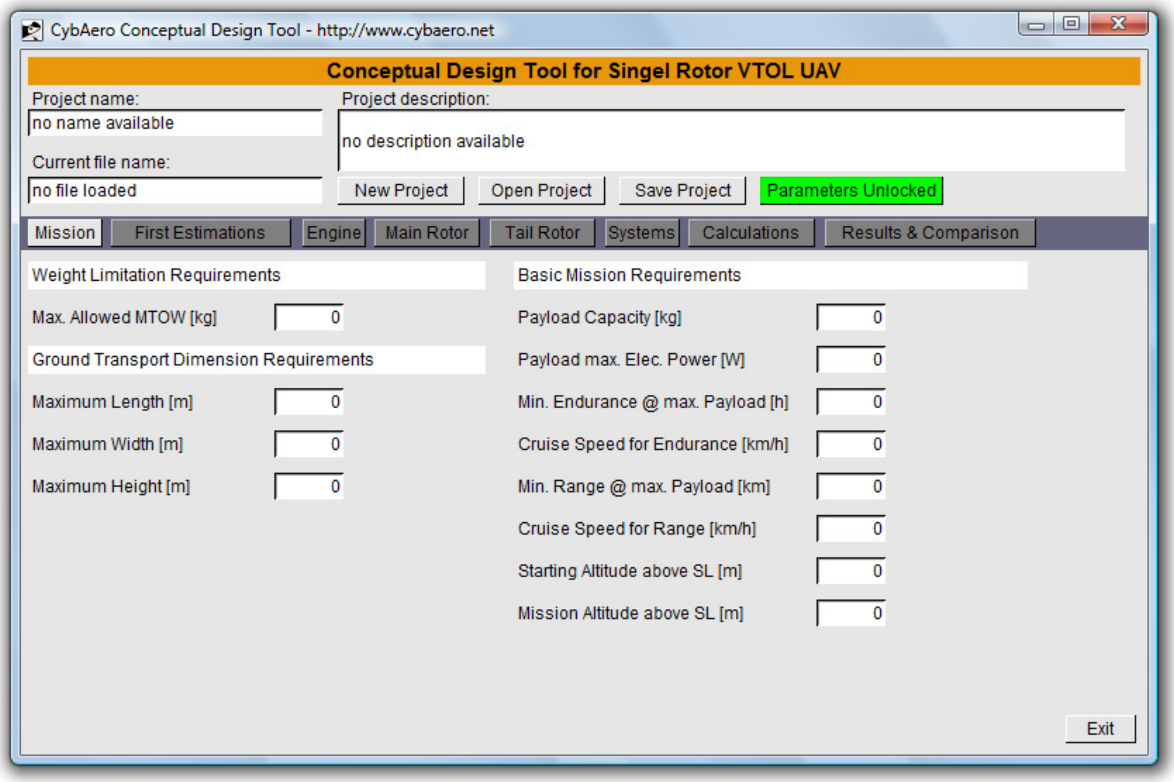
VTOL UAV - Conceptual Design Tool

By: Daniel Moëll & Joachim Nordin

http://www.cybaero.net

2008

Figure 5-1. Program start



Project name: no name available

Current file name: no file loaded

Project description: no description available

Weight Limitation Requirements

Max. Allowed MTOW [kg] 0

Ground Transport Dimension Requirements

Maximum Length [m] 0

Maximum Width [m] 0

Maximum Height [m] 0

Basic Mission Requirements

Payload Capacity [kg] 0

Payload max. Elec. Power [W] 0

Min. Endurance @ max. Payload [h] 0

Cruise Speed for Endurance [km/h] 0

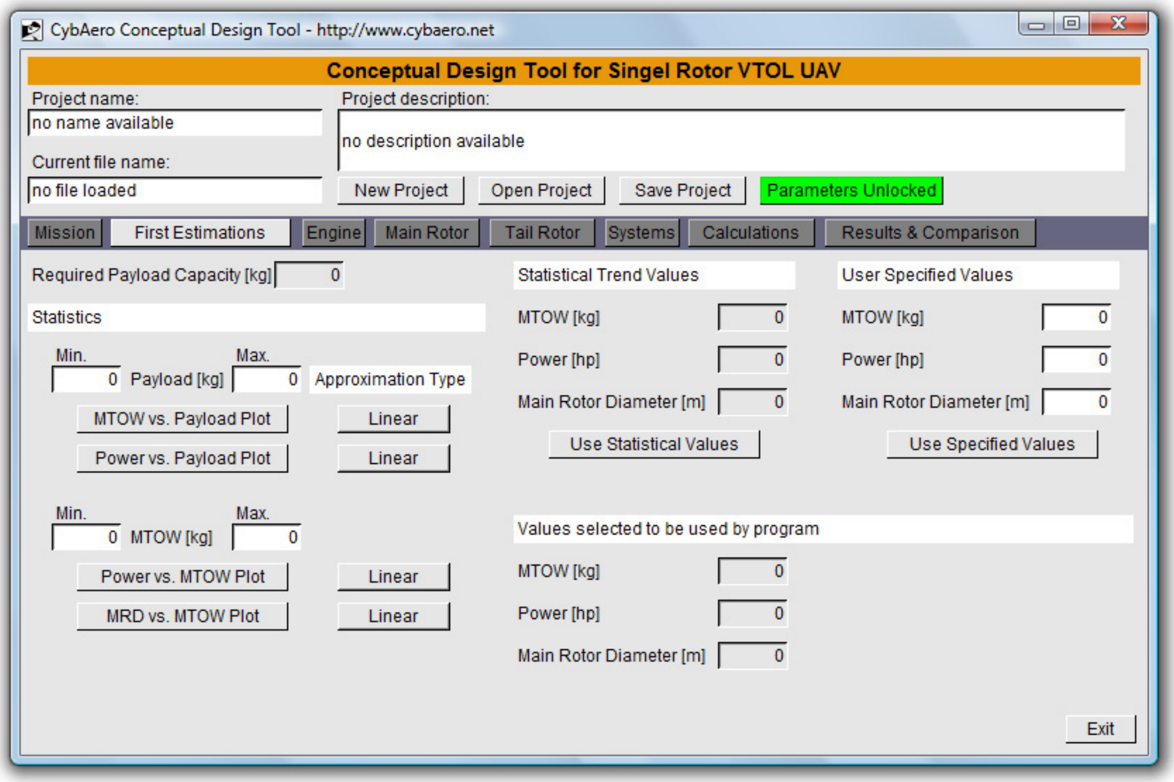
Min. Range @ max. Payload [km] 0

Cruise Speed for Range [km/h] 0

Starting Altitude above SL [m] 0

Mission Altitude above SL [m] 0

Figure 5-2. Mission tab



Project name: no name available

Current file name: no file loaded

Project description: no description available

Required Payload Capacity [kg] 0

Statistics

Min. 0 Payload [kg] Max. 0 Approximation Type

MTOW vs. Payload Plot: Linear

Power vs. Payload Plot: Linear

Min. 0 MTOW [kg] Max. 0

Power vs. MTOW Plot: Linear

MRD vs. MTOW Plot: Linear

Statistical Trend Values

MTOW [kg] 0

Power [hp] 0

Main Rotor Diameter [m] 0

User Specified Values

MTOW [kg] 0

Power [hp] 0

Main Rotor Diameter [m] 0

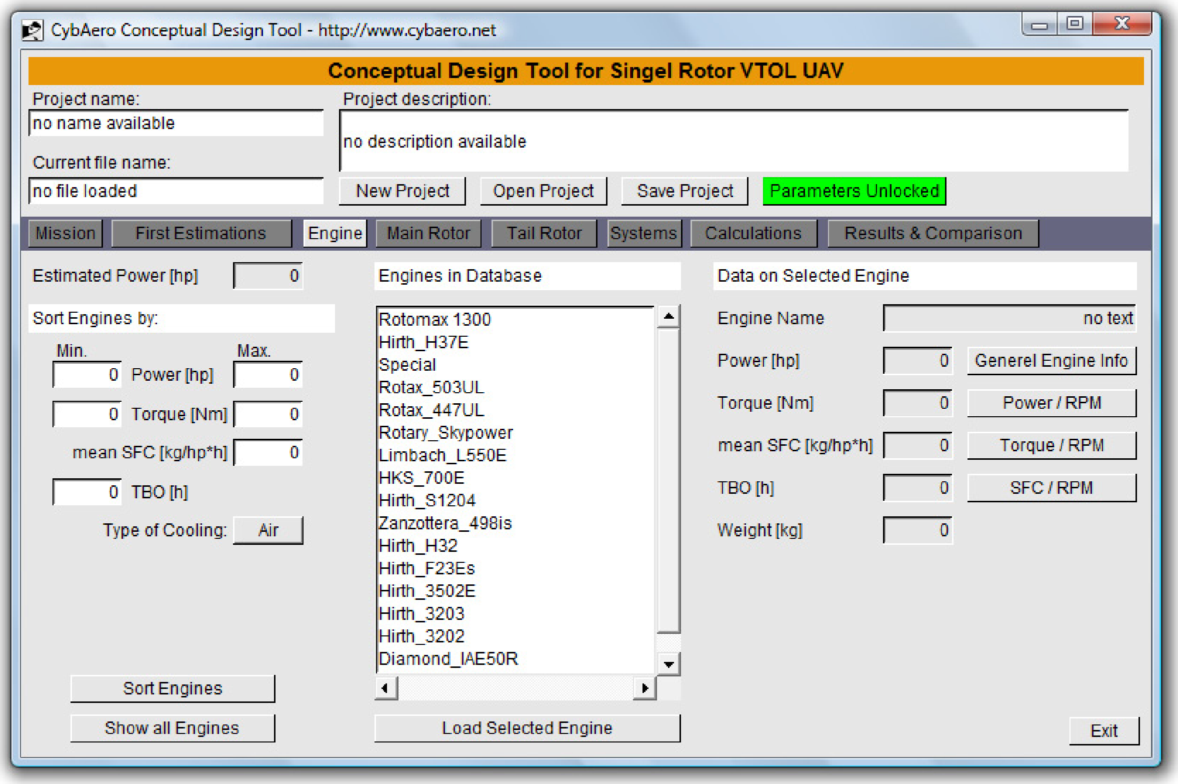
Values selected to be used by program

MTOW [kg] 0

Power [hp] 0

Main Rotor Diameter [m] 0

Figure 5-3. First Estimations tab



Project name: no name available

Current file name: no file loaded

Project description: no description available

Estimated Power [hp] 0

Sort Engines by:

Min.		Max.
0	Power [hp]	0
0	Torque [Nm]	0
	mean SFC [kg/hp*h]	0
0	TBO [h]	

Type of Cooling: Air

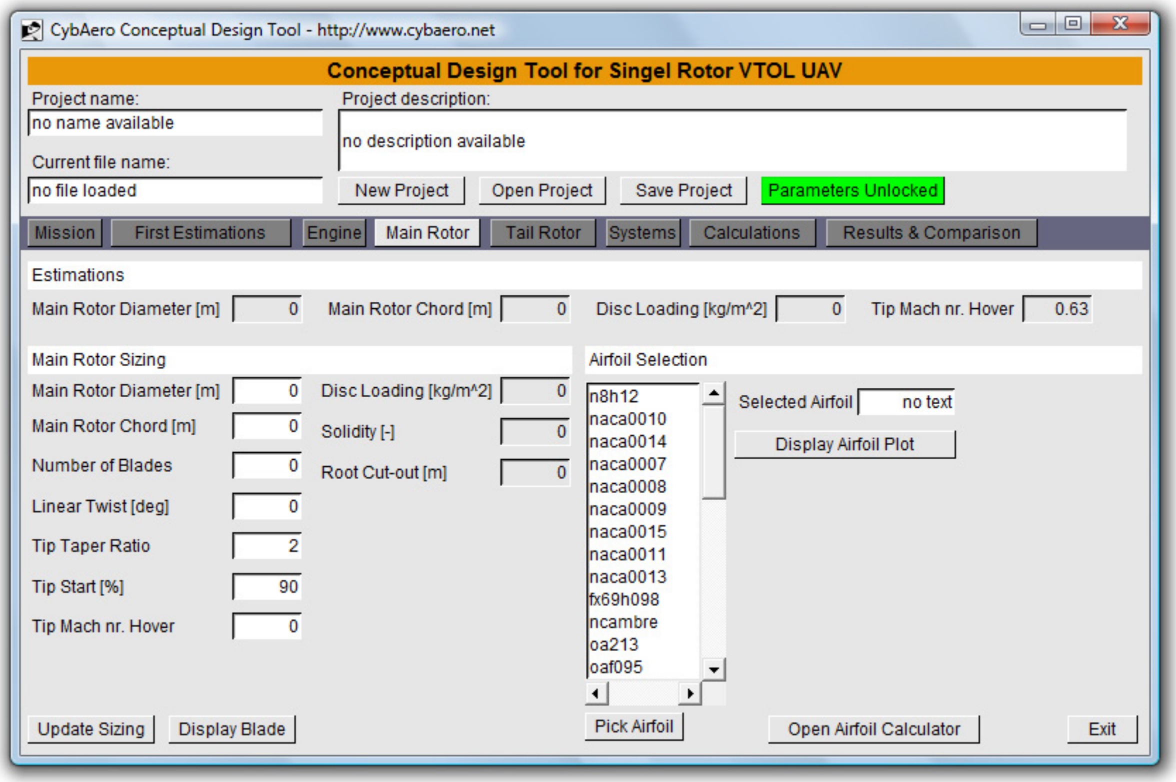
Engines in Database

Rotomax 1300
Hirth_H37E
Special
Rotax_503UL
Rotax_447UL
Rotary_Skypower
Limbach_L550E
HKS_700E
Hirth_S1204
Zanzottera_498is
Hirth_H32
Hirth_F23Es
Hirth_3502E
Hirth_3203
Hirth_3202
Diamond_IAE50R

Data on Selected Engine

Engine Name: no text
Power [hp]: 0
Torque [Nm]: 0
mean SFC [kg/hp*h]: 0
TBO [h]: 0
Weight [kg]: 0

Figure 5-4. Engine tab



Project name: no name available

Current file name: no file loaded

Project description: no description available

Estimations

Main Rotor Diameter [m] 0
Main Rotor Chord [m] 0
Disc Loading [kg/m^2] 0
Tip Mach nr. Hover 0.63

Main Rotor Sizing

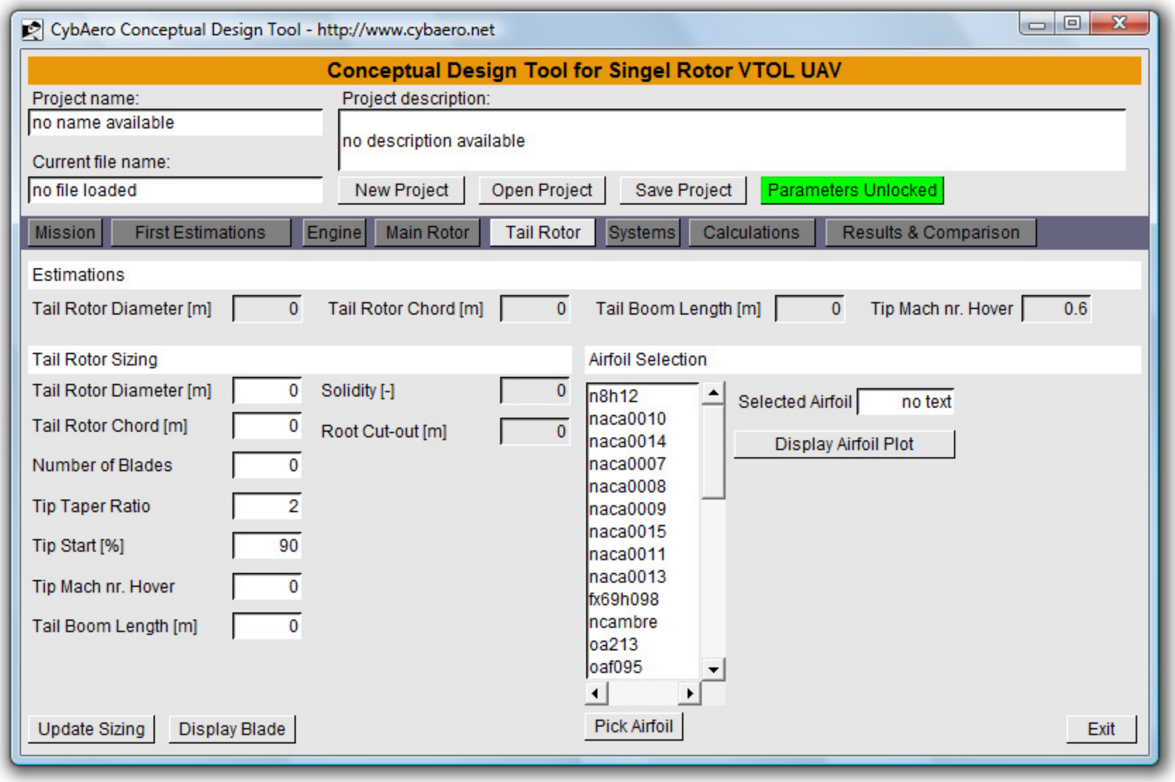
Main Rotor Diameter [m] 0
Main Rotor Chord [m] 0
Number of Blades 0
Linear Twist [deg] 0
Tip Taper Ratio 2
Tip Start [%] 90
Tip Mach nr. Hover 0
Disc Loading [kg/m^2] 0
Solidity [-] 0
Root Cut-out [m] 0

Airfoil Selection

n8h12
naca0010
naca0014
naca0007
naca0008
naca0009
naca0015
naca0011
naca0013
fx69h098
ncambre
oa213
oaf095

Selected Airfoil: no text

Figure 5-5. Main Rotor tab



Project name: no name available

Project description: no description available

Current file name: no file loaded

Estimations

Tail Rotor Diameter [m] 0
Tail Rotor Chord [m] 0
Tail Boom Length [m] 0
Tip Mach nr. Hover 0.6

Tail Rotor Sizing

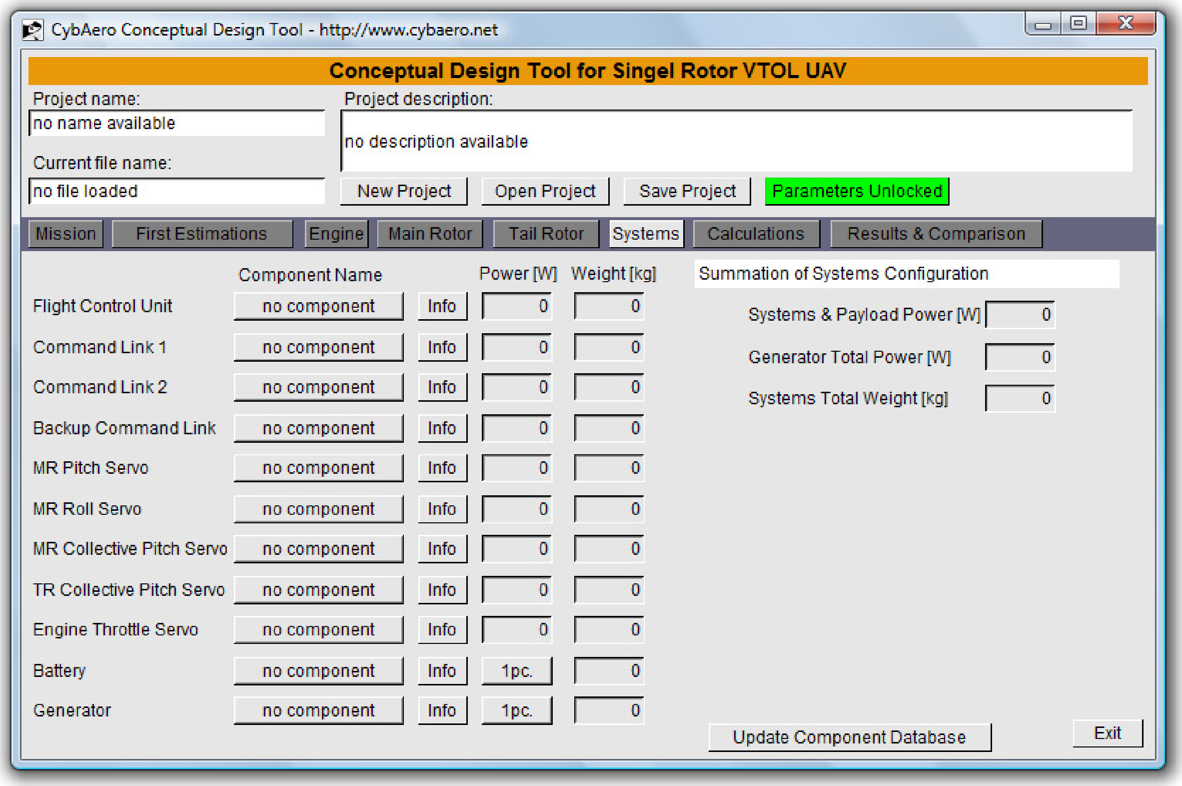
Tail Rotor Diameter [m] 0
Tail Rotor Chord [m] 0
Number of Blades 0
Tip Taper Ratio 2
Tip Start [%] 90
Tip Mach nr. Hover 0
Tail Boom Length [m] 0
Solidity [-] 0
Root Cut-out [m] 0

Airfoil Selection

n8h12
naca0010
naca0014
naca0007
naca0008
naca0009
naca0015
naca0011
naca0013
fx69h098
ncambre
oa213
oaf095

Selected Airfoil no text

Figure 5-6. Tail Rotor tab



Project name: no name available

Project description: no description available

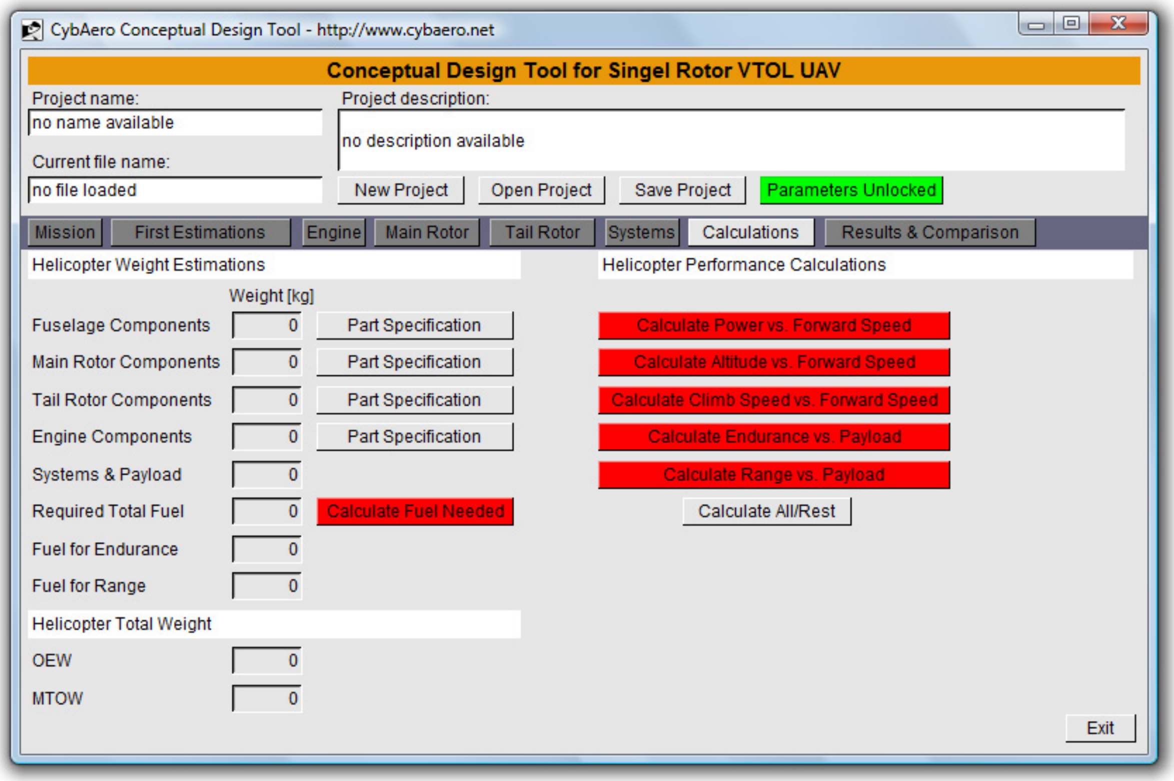
Current file name: no file loaded

	Component Name		Power [W]	Weight [kg]
Flight Control Unit	no component	Info	0	0
Command Link 1	no component	Info	0	0
Command Link 2	no component	Info	0	0
Backup Command Link	no component	Info	0	0
MR Pitch Servo	no component	Info	0	0
MR Roll Servo	no component	Info	0	0
MR Collective Pitch Servo	no component	Info	0	0
TR Collective Pitch Servo	no component	Info	0	0
Engine Throttle Servo	no component	Info	0	0
Battery	no component	Info	1pc.	0
Generator	no component	Info	1pc.	0

Summation of Systems Configuration

Systems & Payload Power [W] 0
Generator Total Power [W] 0
Systems Total Weight [kg] 0

Figure 5-7. Systems tab



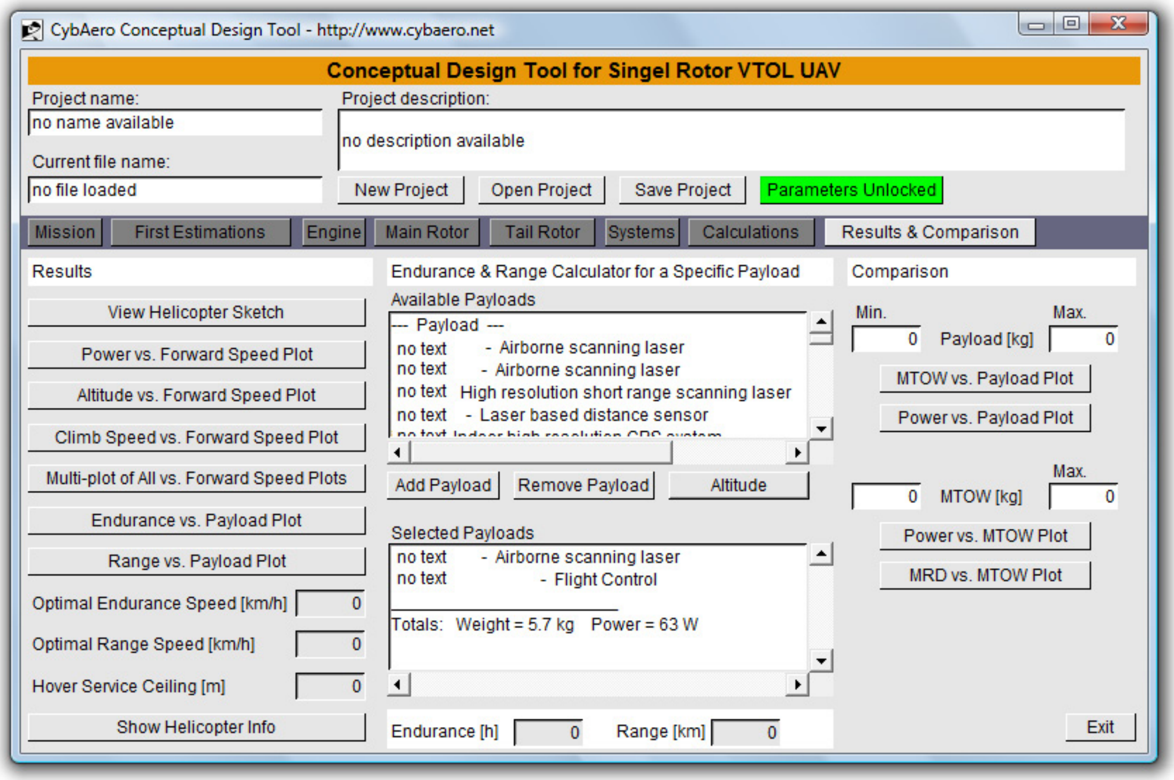
Project name: no name available

Project description: no description available

Current file name: no file loaded

	Weight [kg]
Fuselage Components	0
Main Rotor Components	0
Tail Rotor Components	0
Engine Components	0
Systems & Payload	0
Required Total Fuel	0
Fuel for Endurance	0
Fuel for Range	0
OEW	0
MTOW	0

Figure 5-8. Calculations tab



Project name: no name available

Project description: no description available

Current file name: no file loaded

Optimal Endurance Speed [km/h] 0

Optimal Range Speed [km/h] 0

Hover Service Ceiling [m] 0

Available Payloads:

--- Payload ---
no text - Airborne scanning laser
no text - Airborne scanning laser
no text High resolution short range scanning laser
no text - Laser based distance sensor

Selected Payloads:

no text - Airborne scanning laser
no text - Flight Control

Totals: Weight = 5.7 kg Power = 63 W

Endurance [h] 0 Range [km] 0

Payload [kg] Min. 0 Max. 0

MTOW [kg] 0 Max. 0

Figure 5-9. Results & Comparison tab

5.2 Calculations

In the Design Tool several calculations are performed in different parts of the program. In general there are three big parts of the program in which most of the calculations are done, the parts are:

- Weight Estimations
- Fuel Calculations
- Performance Calculations

The accuracy of the calculations is almost always a compromise between calculation time and calculation accuracy. For example a helicopter flight training simulator needs to be really fast and therefore the accuracy might suffer, on the other side a launch simulation of a space shuttle needs to have a good accuracy on the calculations and the calculation time will suffer.

5.2.1 Weight Estimations

The weight estimations in the program are mainly based on CybAero's two helicopters, which mean that the weight scaling will mostly reflect the weight break-down of those two helicopters. Due to sensitive information the data can't be published. If detailed weight data from other helicopters also would have been used the weight scaling probably would have been of a more general nature for VTOL UAVs. Tests conducted on the weight scaling have proved good agreement between estimated weights and actual weights with a difference around 5-10% for different helicopters tested.

5.2.2 Fuel Calculations

As mentioned previously compromises in the calculations regarding accuracy have to be made to get fast calculations. The results from the fuel weight calculations would probably have been more accurate if each mission had been divided into more parts so that the fuel weight calculation would have represented an integral better.

5.2.3 Performance Calculations

Since all the integrals are calculated numerically some errors will occur. The two parameters affecting the solution most are number of blade elements and Azimuth spacing:

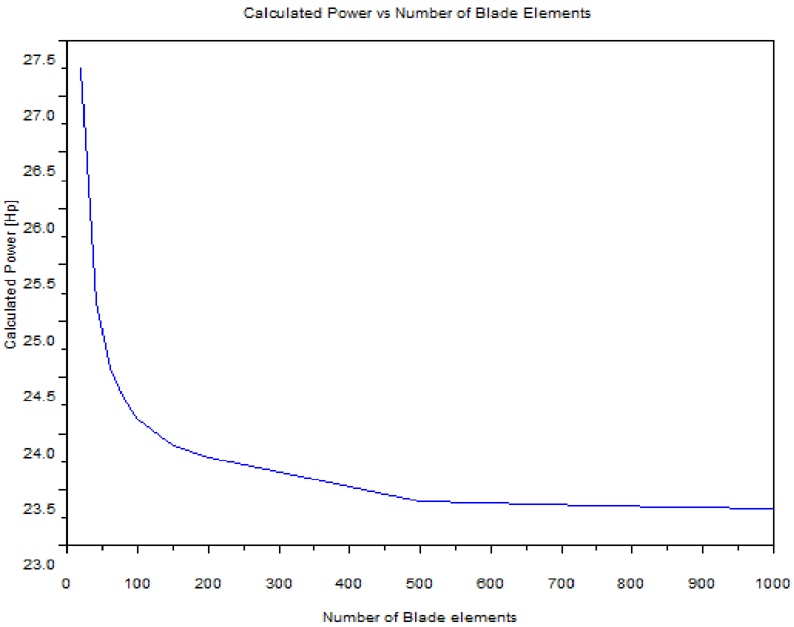


Figure 5-10. Calculated power versus number of blade elements

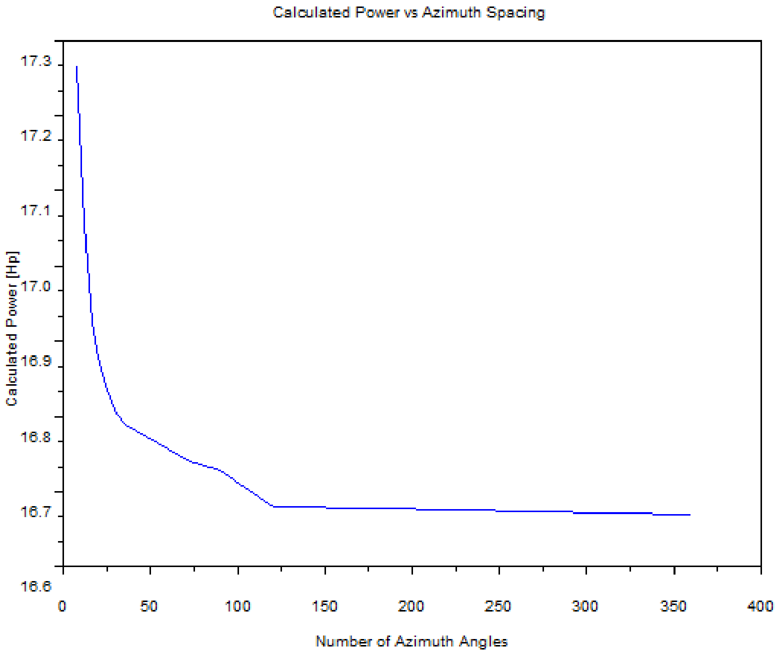


Figure 5-11. Calculated power versus number of Azimuth positions

As shown in Figure 5-10 and Figure 5-11 the calculated power is mostly dependent on the number of blade elements used in the solver. The result varies because of the simple but convergent integration method used in the program. The error occurs at the “ends” of the integration and will therefore be smaller if the end parts are smaller, that is why the result converges into a horizontal line when the number of blade elements increases. The problem with many blade elements is that if the number of elements is doubled the calculation time is doubled. It is recommended to use at least 50 blade elements for acceptable accuracy.

The Azimuth spacing is not as important as the blade elements but it still affects the solution. For the Azimuth integration no real integration is used instead the mean value of all the Azimuth positions is calculated. A good compromise between calculation accuracy and calculation time is 24 Azimuth positions which corresponds to a spacing of 15°.

In order to validate the performance calculator an existing UAV helicopter was put into the calculator. Due to sensitive information the actual values can't be published but the general appearances of the curves are:

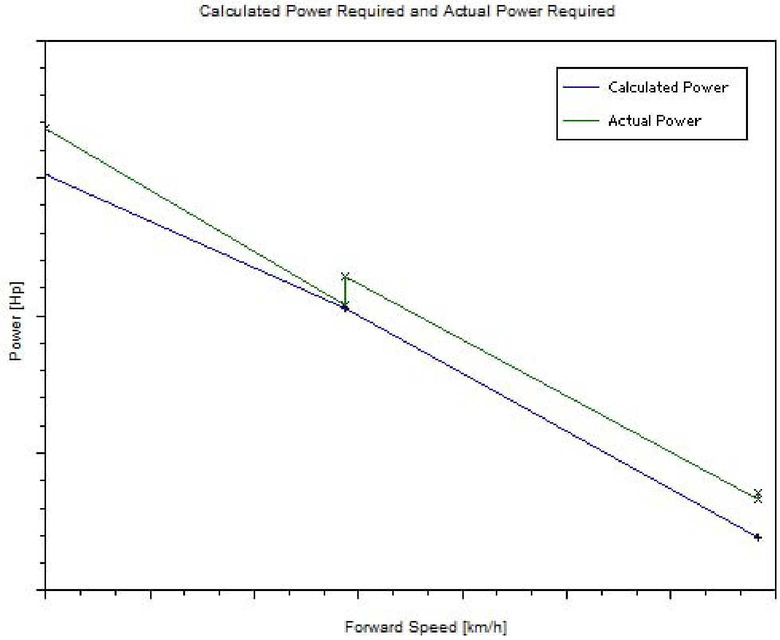


Figure 5-12. Calculated power and actual power at forward flight

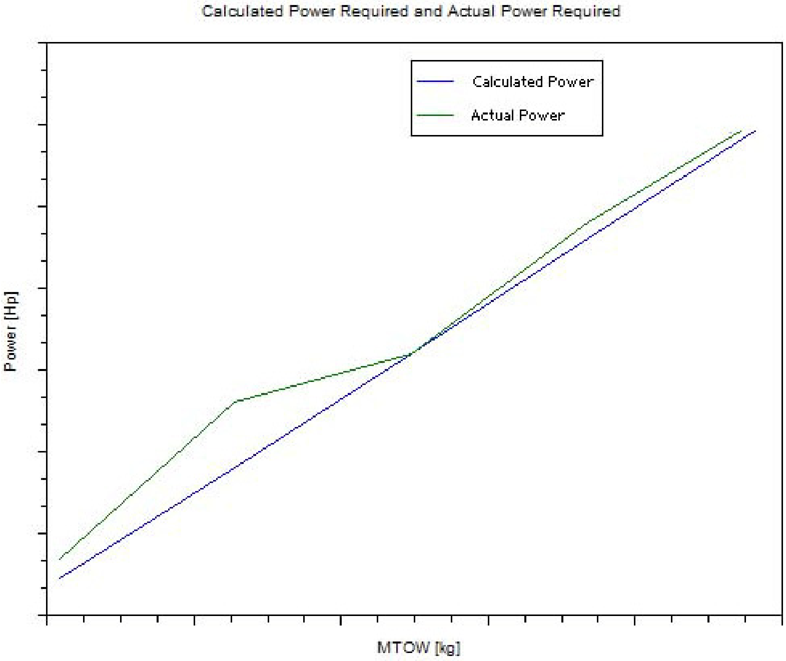


Figure 5-13. Calculated power and actual power at hover

The power versus forward speed comparison in Figure 5-12 is in the speed range before the "turning point" of a general power curve like the one in Figure 5-14.

In Figure 5-12 and Figure 5-13 it can be seen that the theory and the actual performance are very similar. In normal flight conditions the difference in power between calculated and actual power is about 5%. If the number of blade elements and Azimuth positions are changed the calculated curve will simply move up or down but still maintain its appearance.

5.3 Design Restrictions

The design parameters have been slightly restricted in order to get an easy to use program for the purpose of conceptual design. Of course it is possible to make the restrictions as few as possible but by making the program input more complex the ability to compare and evaluate many different concepts is decreased.

5.4 Output from the Design Tool

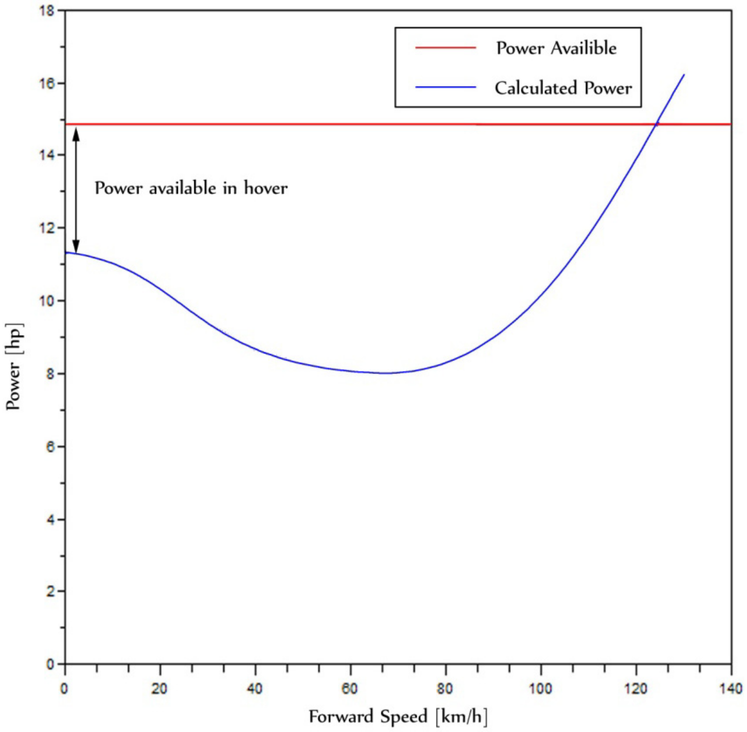


Figure 5-14. Power versus forward speed

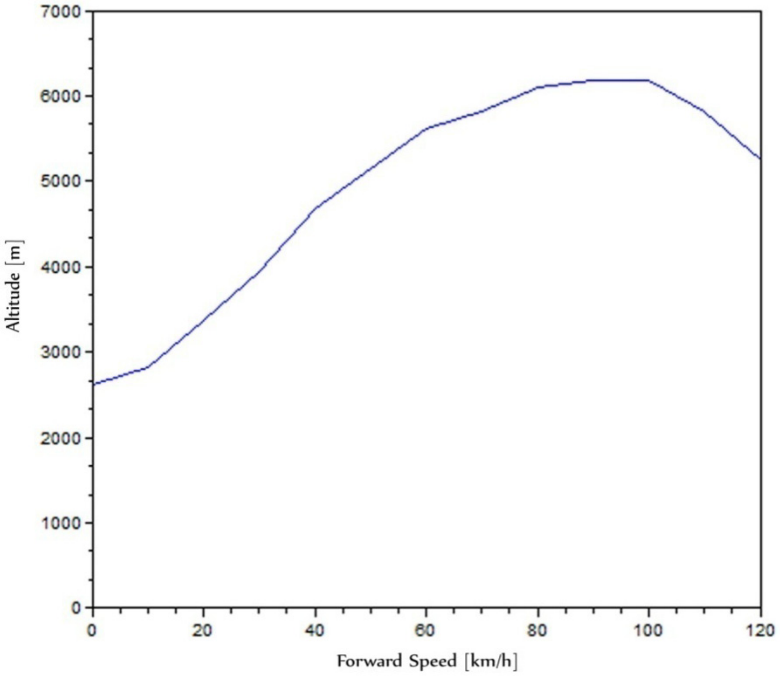


Figure 5-15. Altitude versus forward speed

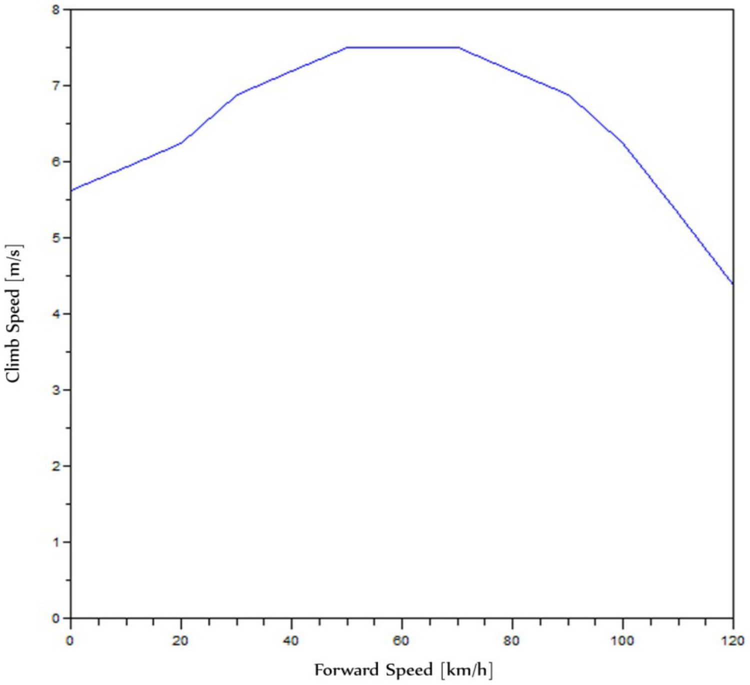


Figure 5-16. Climb speed versus forward speed

In Figure 5-14, 5-15 and 5-16 it can be seen that maximum climb speed and maximum altitude is more or less a direct result from the power versus forward speed curve. The appearance of the climb speed curve also depends on the available power in hover. If the available power is small the maximum climb speed curve tends to have a parabolic shape and if the available power in hover is big the curve tends to be almost horizontal in the beginning. If the available power in hover is too small the helicopter is more or less useless since all the power is consumed by just hovering and no advanced movements can be made.

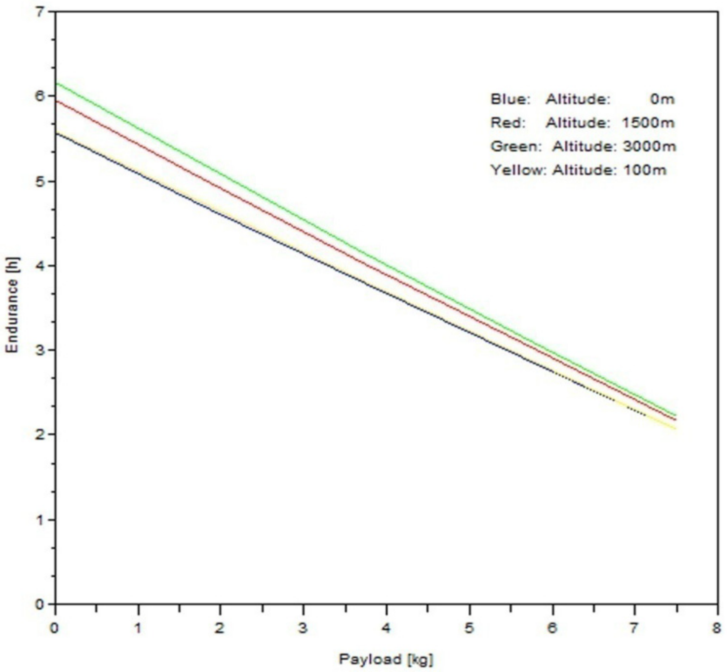


Figure 5-17. Endurance versus payload

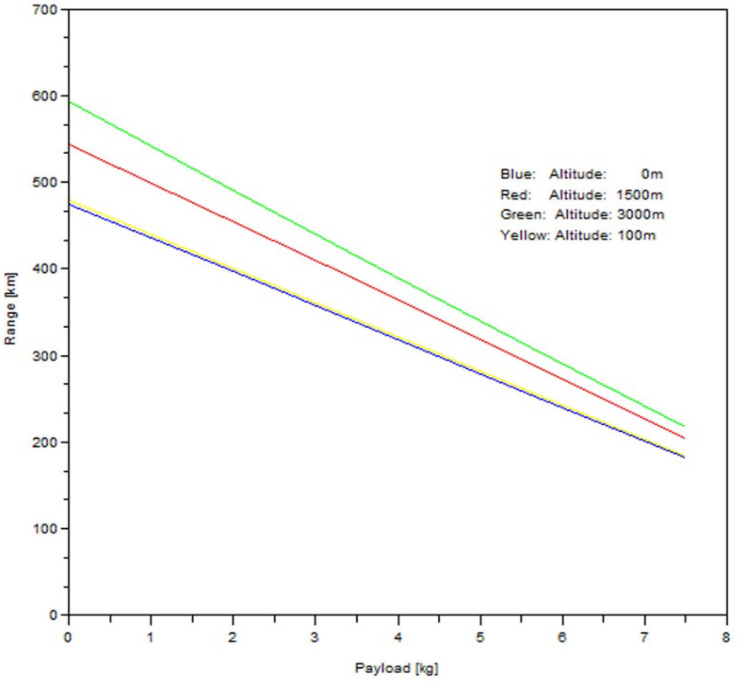


Figure 5-18. Range versus payload

The results in Figure 5-17 and 5-18 are not surprising. If the payload is exchanged with fuel the helicopter maintains the same MTOW but the amount of fuel is increased. The endurance and range will both increase if more fuel is available. The results are highly misleading if the payload is not replaced with fuel or in worst case if the payload is changed for a balancing weight.

6th Chapter
Conclusions & Future Work

The outline of this thesis is that it is possible to make a user friendly Conceptual Design Tool for VTOL UAVs. The design procedure in the Design Tool is relatively simple and the time from start to a complete concept is relatively short. The user does not necessarily need to be a helicopter expert in order to create a complete helicopter concept, instead the statistical database can be used to design a concept for a certain mission specification. If however the user is an expert in helicopter design the concept design can be created rather freely.

It has also been shown that the results from the Design Tool and actual performance results from real helicopters match well.

The next step for the Design Tool is to use more sophisticated methods for the calculations and the estimations in the program. The rotor aerodynamics can be modeled by use of CFD. By using CFD the rotor can be made almost as complex as the user wants to and the interactions between the main rotor and the tail rotor can be evaluated, also the interaction of the fuselage and the main rotor can be evaluated in a better way. For a design point of view it is possible to connect a CAD program and a FEM solver to the Design Tool. This would make it possible to optimize the structural design and the shape of the helicopter. Also the weight estimations could be made directly in the CAD program if the geometries and materials are known. Another evolutionary step for the program could also be to include more requirements such as cost goals. Finally if CFD, CAD and FEM are connected together an optimization algorithm could be made to find the best and most efficient helicopter that fulfills the requirements.

When a good Conceptual Design Tool has been made it would be convenient to have a design evaluation program. For a design evaluation program the performance calculator could be used and the basic structure of the graphical user interface could also be used. The weight estimation is not necessary since the design is already complete. The mission part would be extended to let the user build basically any mission possible. This sort of tool would be very useful for a sales department when performance related questions are asked by customers, it would also be useful in order to plan missions for the helicopter. If an evaluation program is built up it is also possible to load real helicopters into the program and get the performance for a specific mission.

References

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[2] J. Gordon Leishman *"Principles of helicopter aerodynamics - SE"* Cambridge aerospace series, 2006.

[3] Raymond W. Prouty *"Helicopter performance, stability, and control"* Krieger publishing company, 1995.

[4] Kristian Amadori *"On aircraft conceptual design – A framework for knowledge based engineering and design optimization"* Linköping University, Institute of technology, Sweden 2008.

[5] V. Parenzanovic, B. Rasuo, M. Adzic *"Design of Airfoils for Wind Turbines Blades"* University of Belgrade, Serbia

[6] Andrew Bellocchio *"Drive System Design Methodology for a Single Main Rotor Heavy Lift Helicopter"* Georgia Institute of Technology, USA 2005

[7] Clifford Matthews *"Aeronautical Engineer's Data Book"* Butterworth-Heineman 2002

[8] Scilab – http://www.scilab.org – 2008-07-14

[9] GNU GPL License agreements – http://www.gnu.org/copyleft/gpl.html – 2008-07-19

[10] XFOIL – http://web.mit.edu/drela/Public/web/xfoil/ – 2008-07-28

[11] Colin Mill "*Practical Theories"* – http://www.w3mh.co.uk/articles/html/csm9-11.htm – 2008-07-15

[12] MySQL – http://www.mysql.com/ – 2008-09-02

Appendix

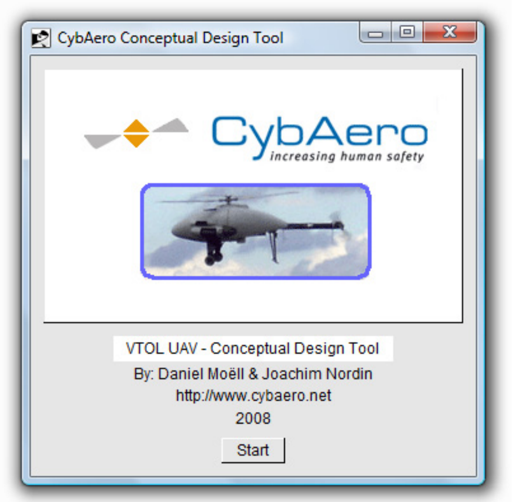
User Manual

"CybAero Conceptual Design Tool" is a computer program intended to be used during the conceptual design phase of new unmanned autonomous single rotor helicopters.

This software is designed to be operated from Scilab version 4.1.2 under the operating systems Windows XP and Windows Vista.

Starting the Software

- Open Scilab version 4.1.2
- In the top menu click "File" → "Change Directory"
- Chose the Conceptual Design Tools "Main Program" folder and click "OK"
- In the top menu click "File" → "Open"
- Chose the file "Program_starter.sce" in the folder "Main Program" and click "OK"
- In the editor "SciPad" click Ctrl + L on the keyboard to launch the software



VTOL UAV - Conceptual Design Tool
By: Daniel Moëll & Joachim Nordin
http://www.cybaero.net
2008

Figure 1. Start screen when the software is launched

General Usage of the Software

The general work order for the program is to go from left to right between tabs and tab-sections. The work order for each tab-section is from the top and down.

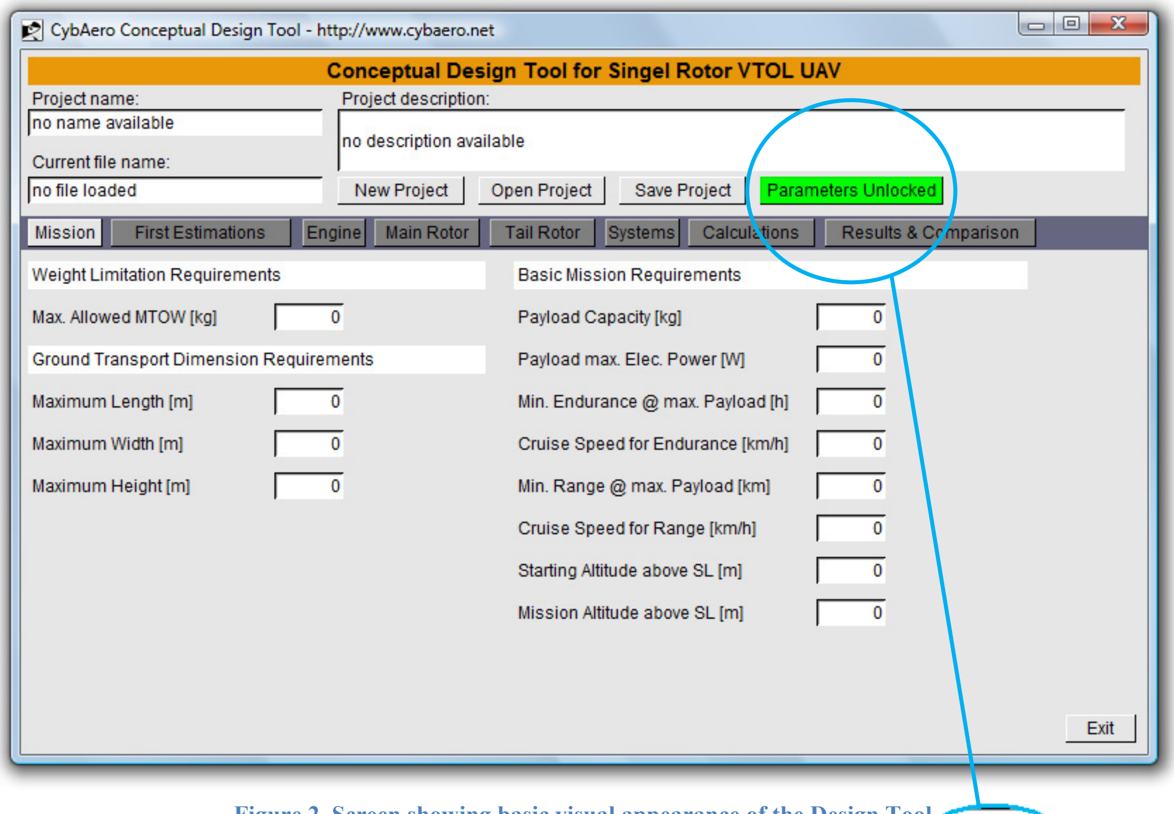
All number inputs into the program should be in English format using dot as decimal separator like 1.3 and not using comma like 1,3.

Number and text input boxes marked with white background color are editable. If they are marked with grey background color they are only display values.

While the program is performing calculations don't change tab.

If the program should hang up during a calculation the calculation can be aborted by clicking Ctrl + C in the Scilab terminal window.

Basic Features



CybAero Conceptual Design Tool - http://www.cybaero.net

Conceptual Design Tool for Singel Rotor VTOL UAV

Project name: no name available

Current file name: no file loaded

Project description: no description available

Weight Limitation Requirements

Max. Allowed MTOW [kg]: 0

Ground Transport Dimension Requirements

Maximum Length [m]: 0

Maximum Width [m]: 0

Maximum Height [m]: 0

Basic Mission Requirements

Payload Capacity [kg]: 0

Payload max. Elec. Power [W]: 0

Min. Endurance @ max. Payload [h]: 0

Cruise Speed for Endurance [km/h]: 0

Min. Range @ max. Payload [km]: 0

Cruise Speed for Range [km/h]: 0

Starting Altitude above SL [m]: 0

Mission Altitude above SL [m]: 0

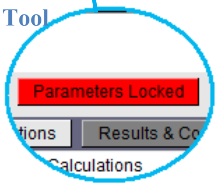
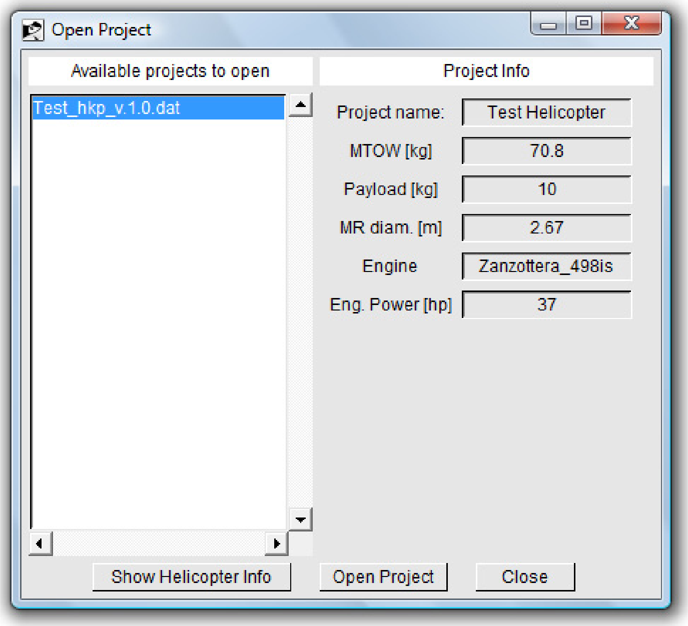


Figure 2. Screen showing basic visual appearance of the Design Tool

The basic features of the program are all located in the top section of the main program window. The basic features consist of commands to save and open projects and to start new ones. Each project can be specified by a file name, project name and a short description. It is possible to activate a parameter lock to prevent accidental change of parameter values.



Open Project

Available projects to open

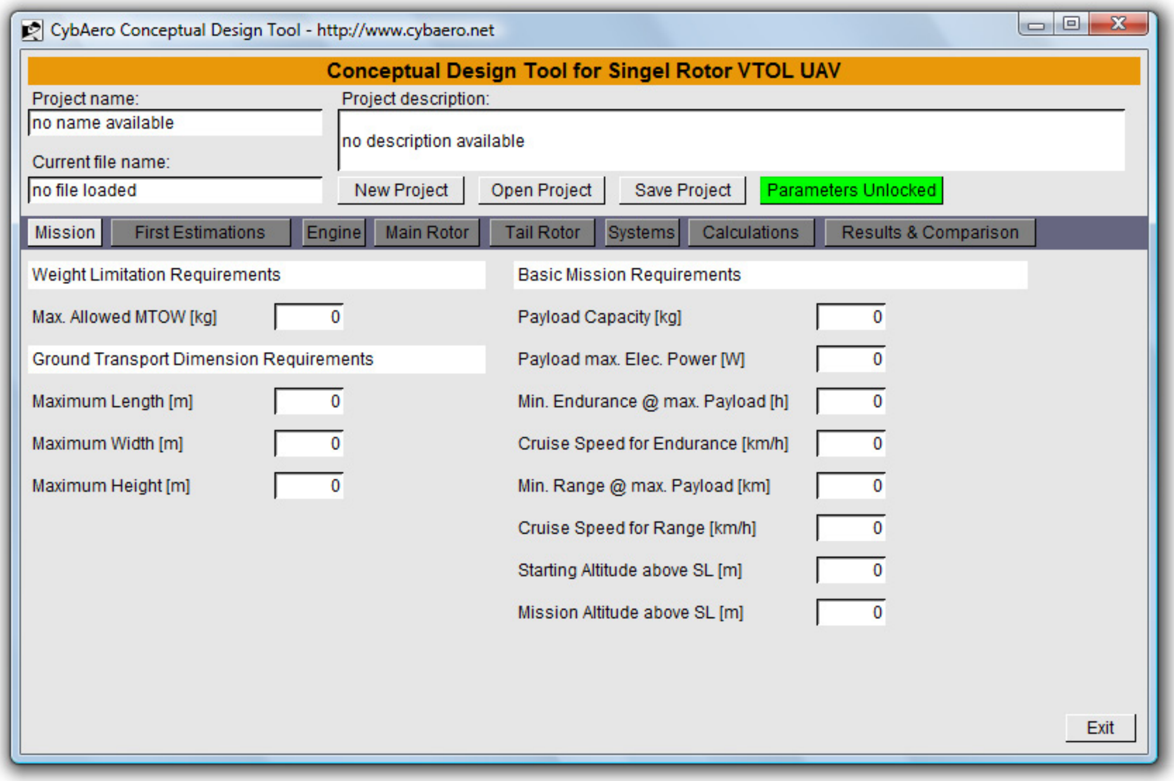
Test_hkp_v.1.0.dat

Project Info

Project name:	Test Helicopter
MTOW [kg]	70.8
Payload [kg]	10
MR diam. [m]	2.67
Engine	Zanzottera_498is
Eng. Power [hp]	37

Figure 3. Window that opens when ”Open Project” button is pushed

Mission Tab



CybAero Conceptual Design Tool - http://www.cybaero.net

Conceptual Design Tool for Singel Rotor VTOL UAV

Project name: no name available

Project description: no description available

Current file name: no file loaded

Weight Limitation Requirements	
Max. Allowed MTOW [kg]	0

Ground Transport Dimension Requirements	
Maximum Length [m]	0
Maximum Width [m]	0
Maximum Height [m]	0

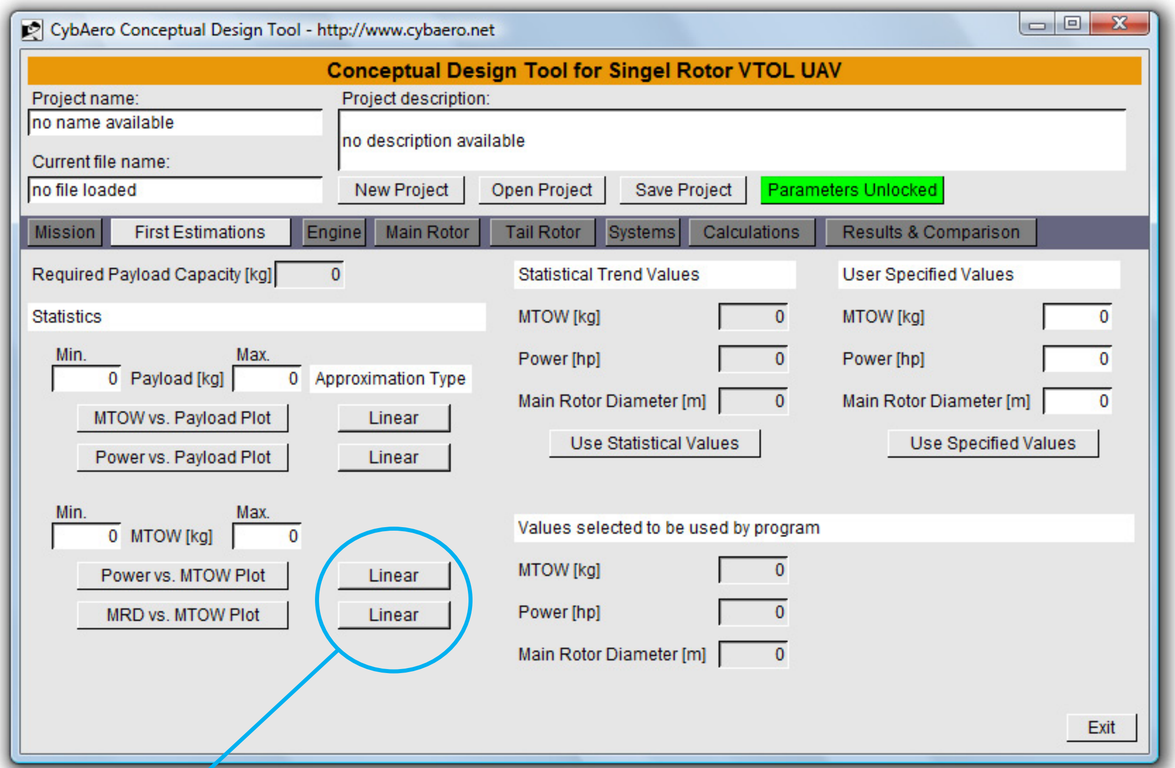
Basic Mission Requirements	
Payload Capacity [kg]	0
Payload max. Elec. Power [W]	0
Min. Endurance @ max. Payload [h]	0
Cruise Speed for Endurance [km/h]	0
Min. Range @ max. Payload [km]	0
Cruise Speed for Range [km/h]	0
Starting Altitude above SL [m]	0
Mission Altitude above SL [m]	0

Figure 4. Main program window with Mission tab activated

Under the mission tab general characteristics that are desired for the helicopter can be specified. It is possible to specify an upper limit of how heavy the helicopter is allowed to be along with dimensions for a ground transport space. The weight limitation is not a design goal for the MTOW only an upper limitation. It can be used to make sure that the helicopter fulfills the weight requirements for a specific helicopter weight class or that it can be lifted by two persons etc. These parameters are optional and if only zeros are filled in they will be neglected by the program.

The basic mission requirements are mandatory and they will “rule” how the design of the helicopter is done. Different requirements give different designs. These requirements are only a rough outline of an endurance mission and a range mission (the mission performance will be calculated separately later in the program). The first thing to specify is a desired payload capacity (maximum payload) and the desired maximum electrical power for the payload. Then the minimum endurance and range desired when carrying maximum payload is specified. Desired speeds for endurance and range are also specified together with starting altitude above ISA sea level and mission altitude above ISA sea level. For the endurance mission the speed must be higher than zero otherwise the program neglects the endurance mission, i.e. endurance can’t be set to be hovering. The climb from start to mission altitude is pre-set in the program with a climb speed of 1 m/s and the forward speed when climbing is calculated so that the most efficient forward speed will be used.

First Estimations Tab



Project name: no name available
Project description: no description available
Current file name: no file loaded

Required Payload Capacity [kg] 0

Statistics

Min. 0 Payload [kg] Max. 0 Approximation Type
MTOW vs. Payload Plot: Linear
Power vs. Payload Plot: Linear

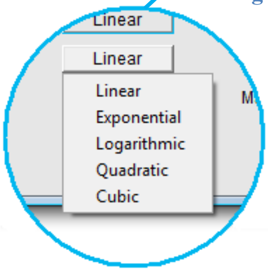
Min. 0 MTOW [kg] Max. 0
Power vs. MTOW Plot: Linear
MRD vs. MTOW Plot: Linear

Statistical Trend Values
MTOW [kg] 0
Power [hp] 0
Main Rotor Diameter [m] 0

User Specified Values
MTOW [kg] 0
Power [hp] 0
Main Rotor Diameter [m] 0

Values selected to be used by program
MTOW [kg] 0
Power [hp] 0
Main Rotor Diameter [m] 0

Figure 5. Main program window with First Estimations tab activated



This tab is optional to fill in but can be used as a guideline in the design work to get a first good estimation of the helicopters general sizing. In the statistical part to the left, plots can be generated to display different relations between general sizing parameters for the helicopter. Different ranges can be selected for payload and MTOW, depending on required payload capacity and estimated MTOW from the first plots. For each plot an approximated curve is generated with curve style according to the user setting.

The statistical trend values in the middle section of the tab are automatically filled in as the plots are generated. As a user of the program it is also possible to fill in your own estimations in the right part of the tab.

In the plots generated each helicopter from the database is represented as a cross. Moving the mouse courser over one of the crosses in the plot and clicking the left mouse button will display which helicopter it is.

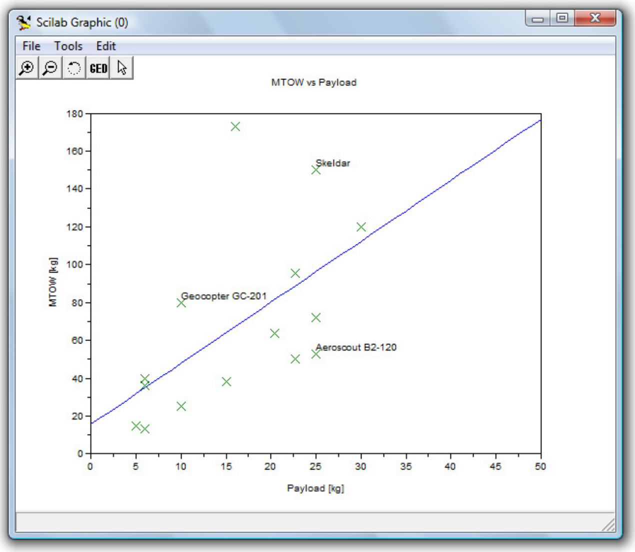
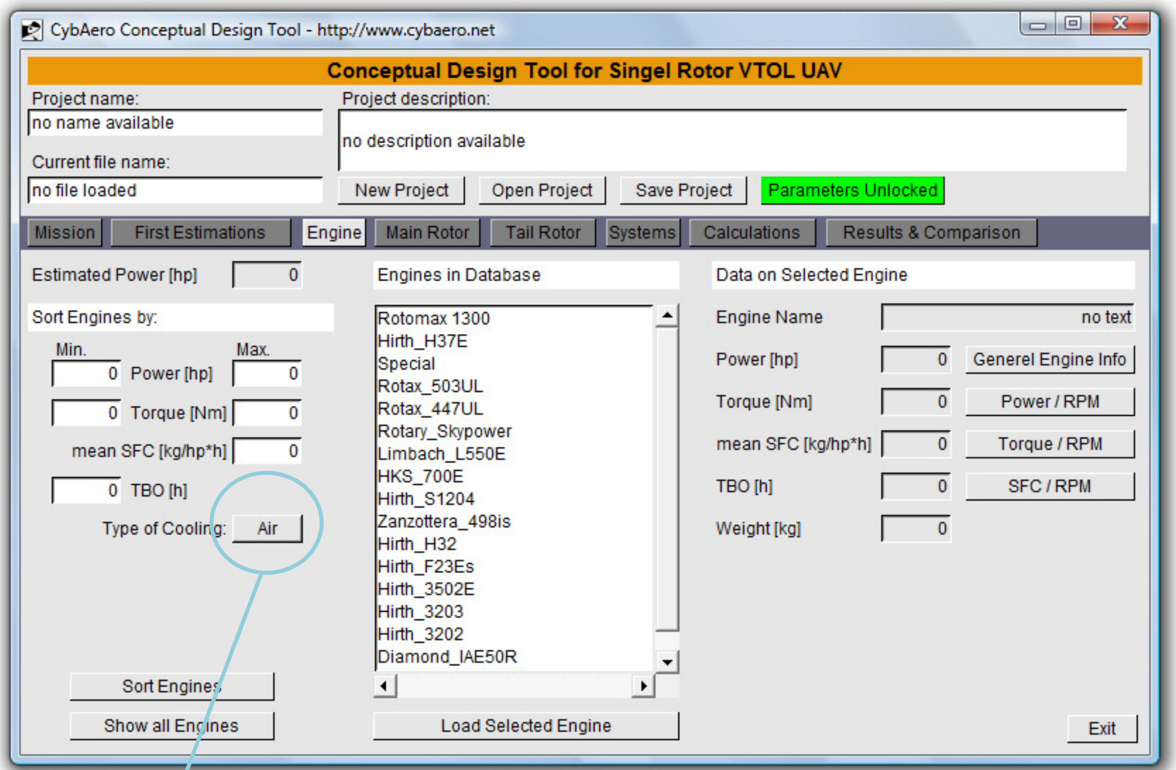


Figure 6. Example plot of MTOW versus payload

Engine Tab



Project name: no name available

Project description: no description available

Current file name: no file loaded

Estimated Power [hp] 0

Power [hp] Min. 0 Max. 0

Torque [Nm] Min. 0 Max. 0

mean SFC [kg/hp*h] 0

TBO [h] 0

Type of Cooling: Air

Rotomax 1300
Hirth_H37E
Special
Rotax_503UL
Rotax_447UL
Rotary_Skypower
Limbach_L550E
HKS_700E
Hirth_S1204
Zanzottera_498is
Hirth_H32
Hirth_F23Es
Hirth_3502E
Hirth_3203
Hirth_3202
Diamond_IAE50R

Engine Name: no text

Power [hp]: 0

Torque [Nm]: 0

mean SFC [kg/hp*h]: 0

TBO [h]: 0

Weight [kg]: 0

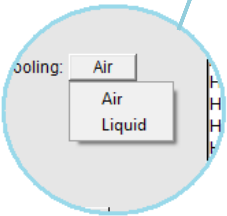
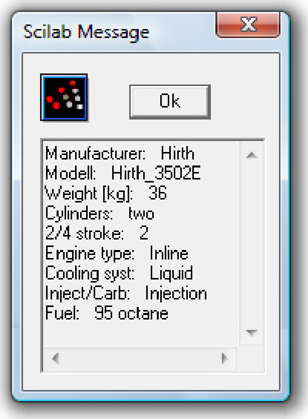


Figure 7. Main program window with Engine tab activated

From the previous tab an estimated engine power is obtained which is used as the basis on the engine tab to select an engine for the helicopter. On the left side of the tab a sorting function is built in to sort out engines that are not suitable to be used.

When a suitable engine has been found it can be loaded into the program from the engine database. It is mandatory to select an engine otherwise the later parts of the program won't work.

Information on the engine can easily be accessed by the buttons on the right side on the engine tab.



Manufacturer: Hirth
Modell: Hirth_3502E
Weight [kg]: 36
Cylinders: two
2/4 stroke: 2
Engine type: Inline
Cooling syst: Liquid
Inject/Carb: Injection
Fuel: 95 octane

Figure 8. General engine info

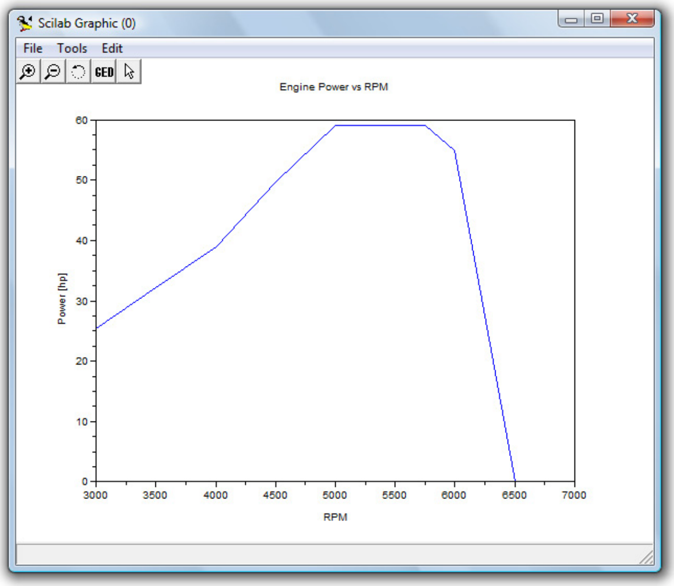
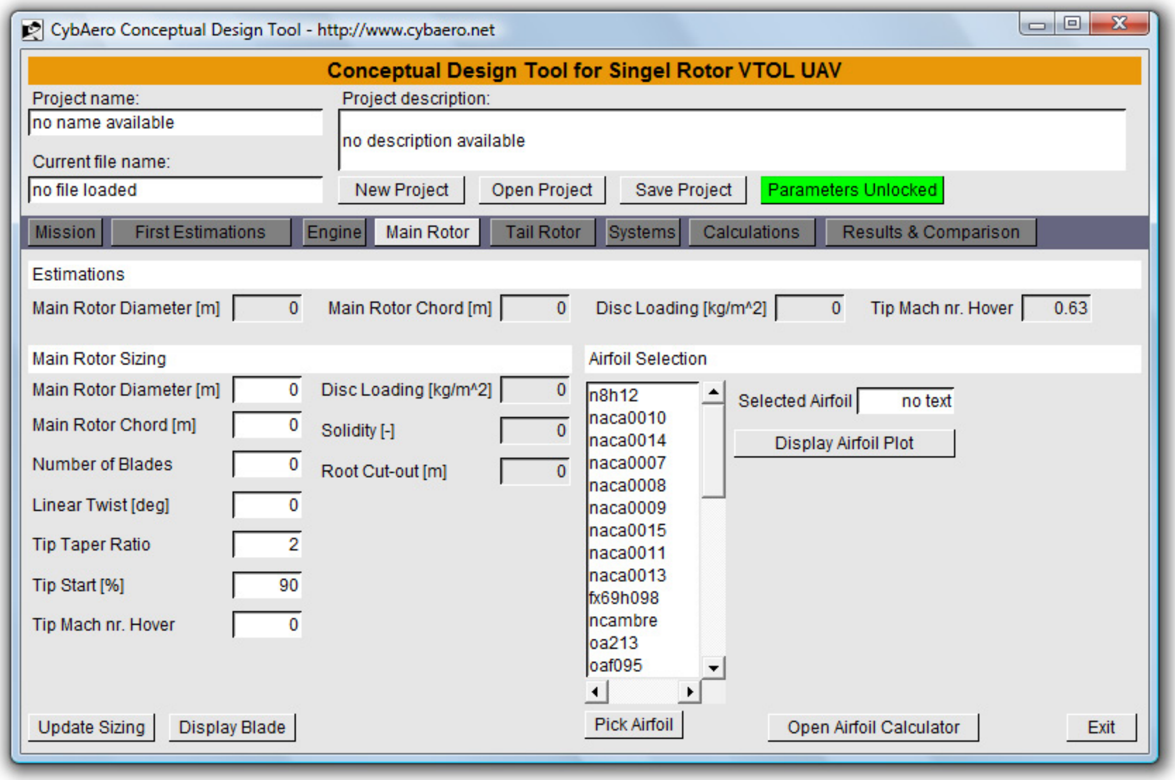


Figure 9. Example plot of engine power versus rpm

Main Rotor Tab



CybAero Conceptual Design Tool - http://www.cybaero.net

Conceptual Design Tool for Singel Rotor VTOL UAV

Project name: no name available

Project description: no description available

Current file name: no file loaded

Estimations

Main Rotor Diameter [m] 0
Main Rotor Chord [m] 0
Disc Loading [kg/m^2] 0
Tip Mach nr. Hover 0.63

Main Rotor Sizing

Main Rotor Diameter [m] 0
Main Rotor Chord [m] 0
Number of Blades 0
Linear Twist [deg] 0
Tip Taper Ratio 2
Tip Start [%] 90
Tip Mach nr. Hover 0
Disc Loading [kg/m^2] 0
Solidity [-] 0
Root Cut-out [m] 0

Airfoil Selection

Selected Airfoil no text

Figure 10. Main program window with Main Rotor tab activated

All parameters on this tab are mandatory for the program to work. The top section of this tab gives guidance to the main rotor design based on the previous estimations done in the program. If you have little experience in helicopter design it is advised to use the values estimated by the program.

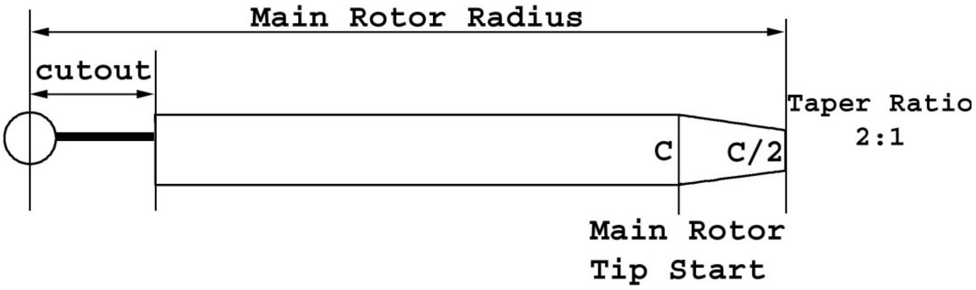
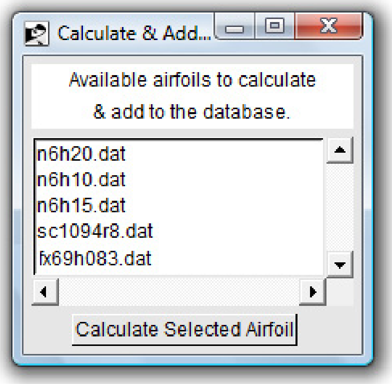


Figure 11. Sketch of a main rotor blade

By clicking on the button "Open Airfoil Calculator" a new window is opened, showing airfoil coordinate files in the database folder that have not yet been calculated and added to the airfoil performance database. By selecting the desired airfoil and clicking on the button "Calculate Selected Airfoil" the airfoil performance is calculated with XFOIL and added to the database so that the airfoil can be used on the rotor blade by the program. New airfoils can easily be added if the coordinate file is given and placed into the "Coordinate files" folder in "Main Program" → "Database" → "Blade airfoils".



Calculate & Add...

Available airfoils to calculate & add to the database.

It is important that the airfoil coordinate file is on the right format so that it can be read by XFOIL in the right way, please read the XFOIL manual for further instructions.

The button “Display Blade” will generate a simple top view sketch of the rotor. An example plot can be seen in Figure 12.

The button “Display Airfoil Plot” generates a plot of the selected airfoil. An example plot can be seen in Figure 13.

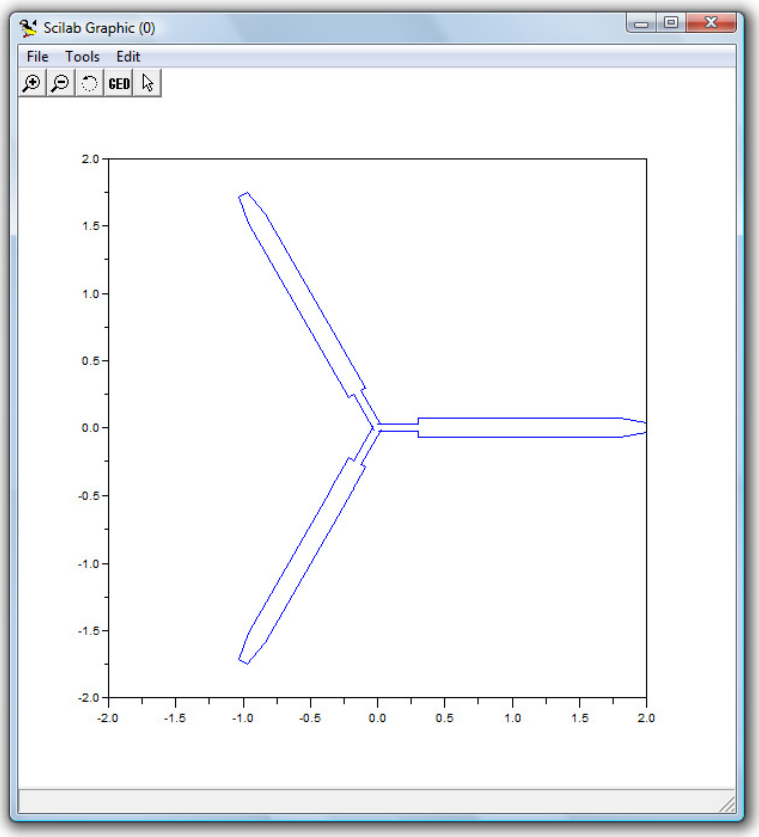


Figure 12. Example plot of the rotor blades

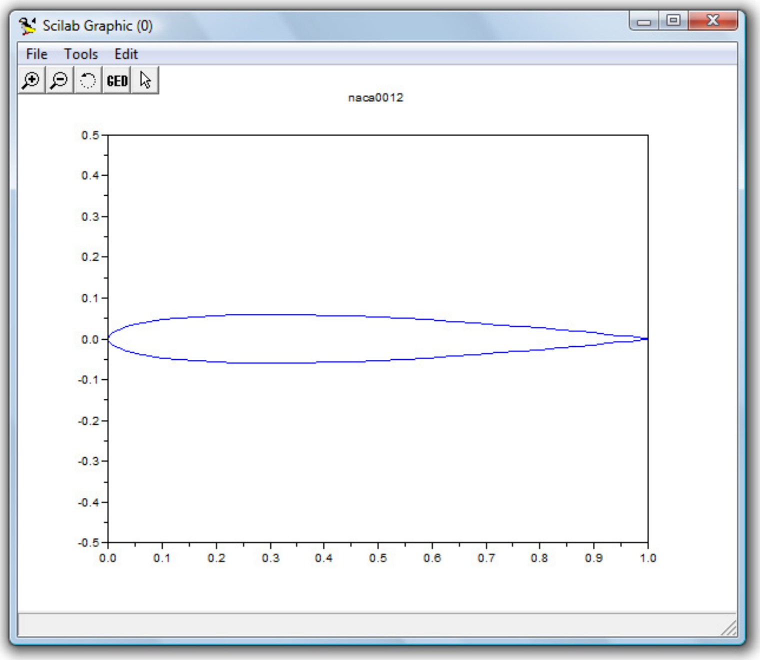
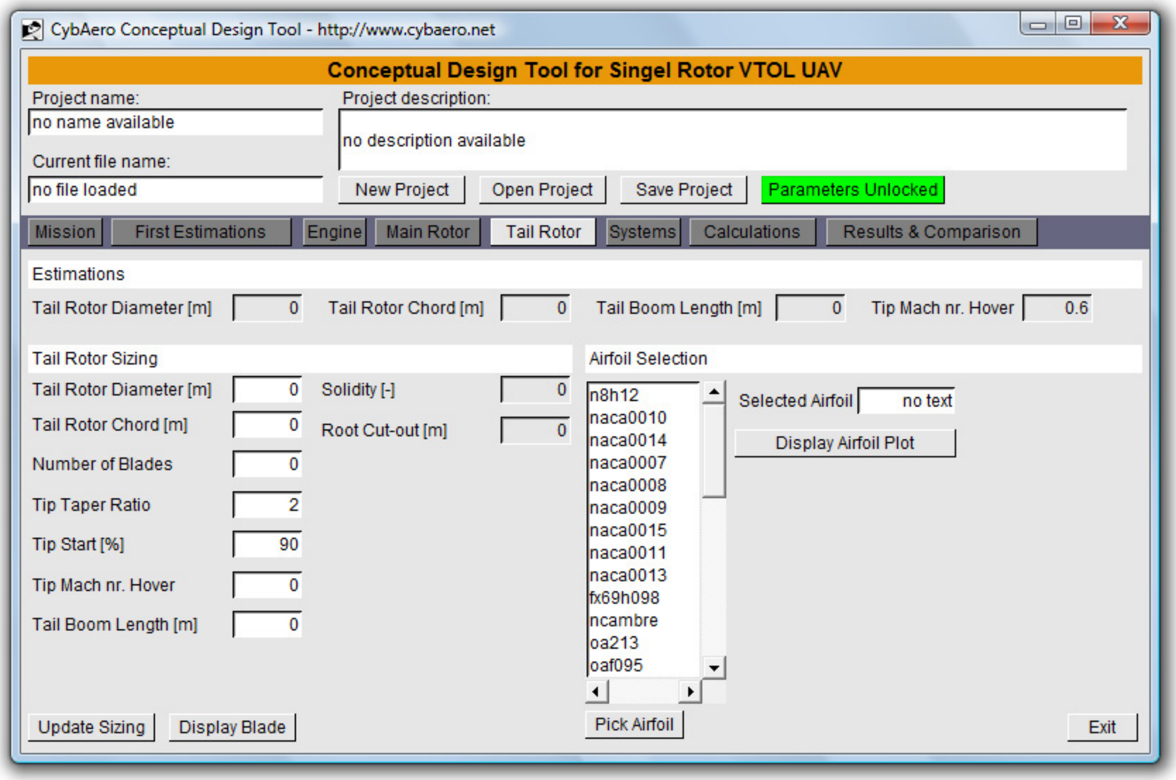


Figure 13. Example plot of an airfoil

Tail Rotor Tab



CybAero Conceptual Design Tool - http://www.cybaero.net

Conceptual Design Tool for Singel Rotor VTOL UAV

Project name: no name available

Current file name: no file loaded

Project description: no description available

Estimations

Tail Rotor Diameter [m] 0
Tail Rotor Chord [m] 0
Tail Boom Length [m] 0
Tip Mach nr. Hover 0.6

Tail Rotor Sizing

Tail Rotor Diameter [m] 0
Tail Rotor Chord [m] 0
Number of Blades 0
Tip Taper Ratio 2
Tip Start [%] 90
Tip Mach nr. Hover 0
Tail Boom Length [m] 0
Solidity [-] 0
Root Cut-out [m] 0

Airfoil Selection

Selected Airfoil no text

Figure 14. Main program window with Tail Rotor tab activated

All parameters on this tab are mandatory for the program to work. The top section of this tab gives guidance to the tail rotor design based on the previous estimations done in the program. If you have little experience in helicopter design it is advised to use the values estimated by the program.

Compared to the main rotor design the design of the tail rotor is simplified by removal of the parameter for blade twist. “Tail Boom Length” is set to be the distance between main rotor shaft and tail rotor shaft as can be seen in Figure 15.

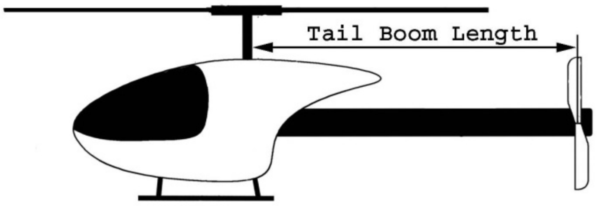
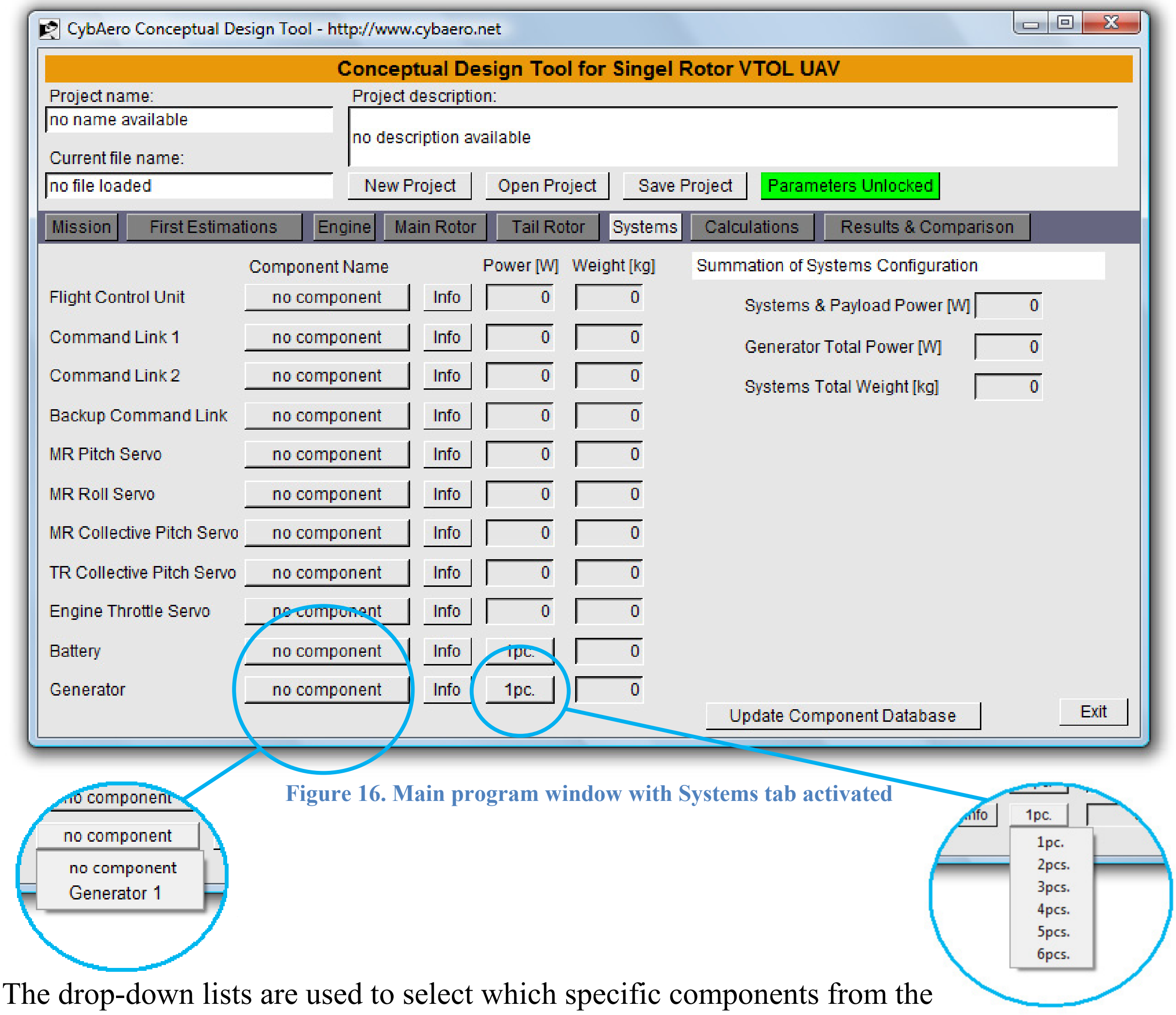


Figure 15. Definition of the parameter “Tail Boom Length”

Systems Tab



CybAero Conceptual Design Tool - http://www.cybaero.net

Conceptual Design Tool for Singel Rotor VTOL UAV

Project name: no name available

Project description: no description available

Current file name: no file loaded

	Component Name		Power [W]	Weight [kg]
Flight Control Unit	no component	Info	0	0
Command Link 1	no component	Info	0	0
Command Link 2	no component	Info	0	0
Backup Command Link	no component	Info	0	0
MR Pitch Servo	no component	Info	0	0
MR Roll Servo	no component	Info	0	0
MR Collective Pitch Servo	no component	Info	0	0
TR Collective Pitch Servo	no component	Info	0	0
Engine Throttle Servo	no component	Info	0	0
Battery	no component	Info	1pc.	0
Generator	no component	Info	1pc.	0

Summation of Systems Configuration

Systems & Payload Power [W] 0

Generator Total Power [W] 0

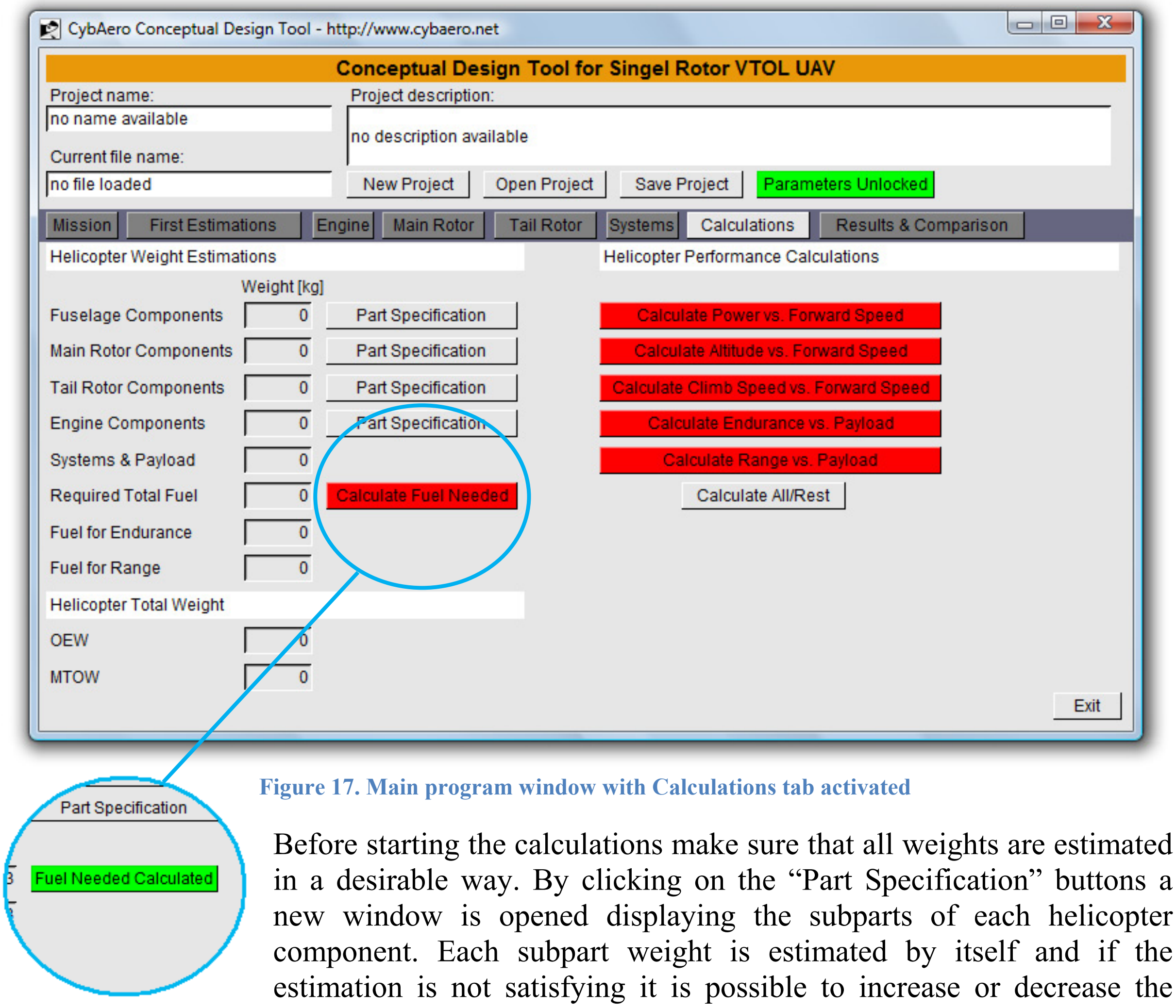
Systems Total Weight [kg] 0

Figure 16. Main program window with Systems tab activated

The drop-down lists are used to select which specific components from the database to use. For the battery and generator the number of units can be selected with another drop-down list.

The button “Update Component Database” will try to connect the software to the database server and download the latest version of the component database. If no connection can be established the database will use the values from the last time an update was made.

Calculations Tab



Project name: no name available

Project description: no description available

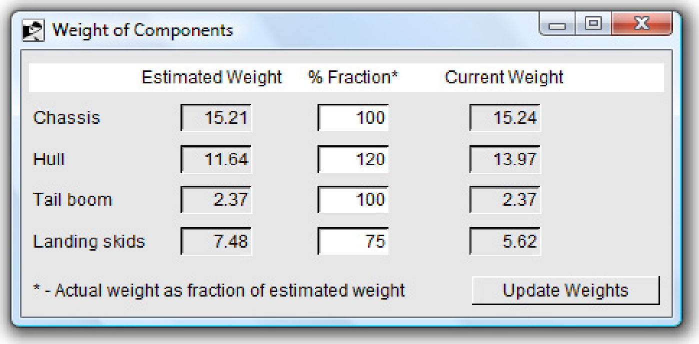
Current file name: no file loaded

	Weight [kg]
Fuselage Components	0
Main Rotor Components	0
Tail Rotor Components	0
Engine Components	0
Systems & Payload	0
Required Total Fuel	0
Fuel for Endurance	0
Fuel for Range	0
OEW	0
MTOW	0

Figure 17. Main program window with Calculations tab activated

Before starting the calculations make sure that all weights are estimated in a desirable way. By clicking on the "Part Specification" buttons a new window is opened displaying the subparts of each helicopter component. Each subpart weight is estimated by itself and if the estimation is not satisfying it is possible to increase or decrease the estimated weight, see Figure 18.

The required fuel first seen when the tab is activated for the first time is only a rough estimation. The "Calculate Fuel Needed" button will start a more accurate estimation of the fuel weight by letting the helicopter "fly" the specified endurance mission and the range mission predicting how much fuel is needed.



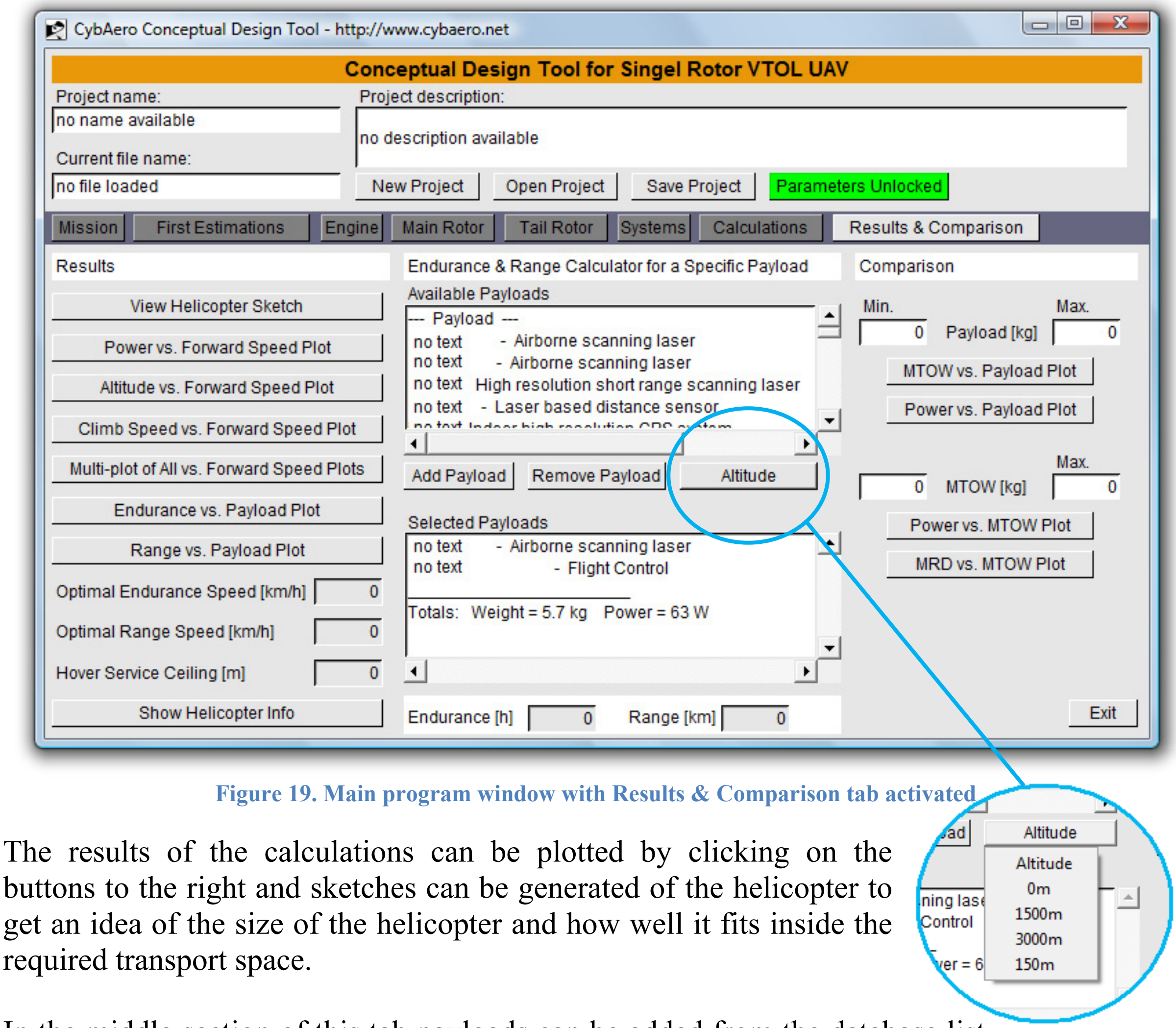
	Estimated Weight	% Fraction*	Current Weight
Chassis	15.21	100	15.24
Hull	11.64	120	13.97
Tail boom	2.37	100	2.37
Landing skids	7.48	75	5.62

* - Actual weight as fraction of estimated weight

Figure 18. Window showing the subparts of the fuselage

The mission requiring most fuel will be dimensioning for the helicopter. When the fuel weight has been calculated the button changes color to green, see Figure 17. The performance calculations for power versus forward speed, altitude versus forward speed etc can now be calculated as the helicopters weight has been predicted. The order of the calculations should be from the top and down. After each calculation have been performed the program auto-saves the project and changes the button color to green indicating that it is finished.

Results & Comparison Tab



CybAero Conceptual Design Tool - http://www.cybaero.net

Conceptual Design Tool for Singel Rotor VTOL UAV

Project name: no name available

Project description: no description available

Current file name: no file loaded

Parameters Unlocked

Available Payloads
--- Payload ---
no text - Airborne scanning laser
no text - Airborne scanning laser
no text High resolution short range scanning laser
no text - Laser based distance sensor

Selected Payloads
no text - Airborne scanning laser
no text - Flight Control

Totals: Weight = 5.7 kg Power = 63 W

Optimal Endurance Speed [km/h] 0

Optimal Range Speed [km/h] 0

Hover Service Ceiling [m] 0

Endurance [h] 0 Range [km] 0

Min. 0 Payload [kg] Max. 0

0 MTOW [kg] Max. 0

Figure 19. Main program window with Results & Comparison tab activated

The results of the calculations can be plotted by clicking on the buttons to the right and sketches can be generated of the helicopter to get an idea of the size of the helicopter and how well it fits inside the required transport space.

In the middle section of this tab payloads can be added from the database list to estimate range and endurance with that specific payload and the selected altitude.

To the right comparison plots can be made showing your helicopter design compared to the helicopters saved in the database.

Adding Information to Databases

In the folder “Data input” located directly in the “Main Program” folder two Excel sheets can be found that is called “Engine data.xls” and “Weight stats.xls”. In the “Engine data” Excel sheet new engines can be added, these new engines will be loaded into the Conceptual Design Tool the next time the program is launched. New helicopter can in the same way be added into the “Weight stats” Excel sheet to further enhance the statistical database and improve the predictions based on statistics.

As mentioned earlier in the manual new airfoils can easily be added if the coordinate file is given and placed into the “Coordinate files” folder in “Main Program” → “Database” → “Blade airfoils”. It is important that the airfoil coordinate file is on the right format so that it can be read by XFOIL in the right way, please read the XFOIL manual for further instructions.

The component database can be updated with standard MySQL query browser or other similar tools able to connect to the MySQL database.