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Conceptual Design of a Vertical Take Off & Landing Unmanned Aerial Vehicle

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Abstract
This paper describes a conceptual design study for a vertical takeoff and landing (VTOL) helicopters. 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 fulfil the goal a compromise between calculation accuracy and calculation time needs to be done. 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 paper 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. Sensitivity analyses were also performed on the requirements and the technology levels to obtain a better understanding of the design space. This study found that within the study assumptions the mission is feasible; the selected concepts are recommended for further development.

Key Word and Phrases
Payload, Endurance, Unmanned Aerial Vehicle, Take off and Landing, Performance, Weight.

1. Introduction

This study was undertaken to explore the possibility of combining two diametrically opposed requirements, specifically, a long-endurance flight with vertical takeoff and landing. 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. The goal of this paper 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. In the initial phase of the paper 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 paper. 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]. When the theory was worked thru and it was figured out how all of the software were working the next step was to implement everything in Scilab.

The final part of the paper was to evaluate the Design Tool against real flight data. Also the robustness of the Design Tool was evaluated. 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 Defence Research Agency (FOI) and Linköping University.

2. 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.[1], [2], [4]

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.[5]

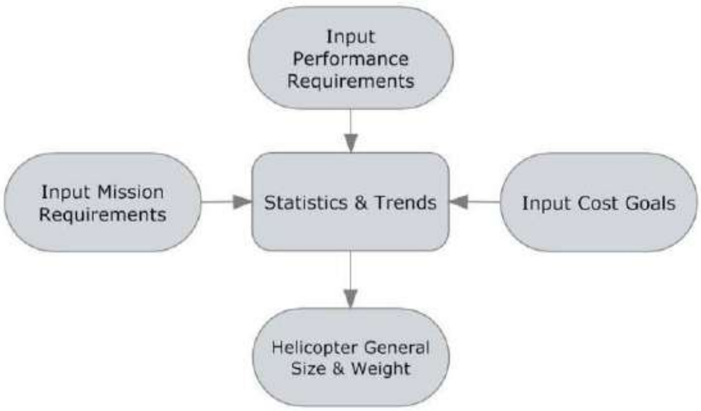

Fig. 1 Flowchart of the first stage in conceptual design process

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[3]. 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.

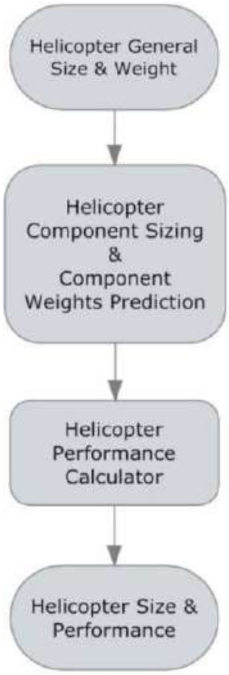

Fig. 2 Flowchart of the last stage in conceptual design process

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 fulfil 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.[7]

3. 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 through the program is described in Figure. 3.

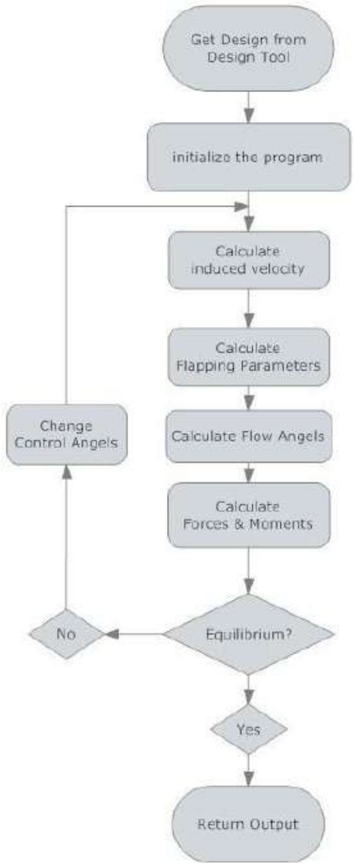

Fig. 3 Flowchart of calculation program

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 chapters 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:

•ΔF = ± 9.5 N

•ΔM = ± 1.55 Nm

If the convergence criterion is not reached the control angles are changed by a scheme based on the nondimensionalized differences in each direction like:[8]

$$\theta_0 = \theta_0 + K_0 - C\Delta vertical/\sigma \tag{3.1}$$

$$\alpha_s = \alpha_s + K_0 - C\Delta longitudinal/\sigma \tag{3.2}$$

$$\beta_s = \beta_s + K_0 - C\Delta lateral/\sigma \tag{3.3}$$

$$A_1 = A_1 + K_0 - C\Delta Pitch/\sigma \tag{3.4}$$

$$B_1 = B_1 + K_0 - C\Delta roll/\sigma \tag{3.5}$$

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. 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.[6], [5]

5. 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.[2], [3]

6. 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.

7. 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.

8. 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.[7]

9. 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.[3]

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.

10. Results & Discussion

In this chapter the results will be displayed and discussed. The main result from this paper 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.[8],[7],[5]

11. Appearance

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

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.

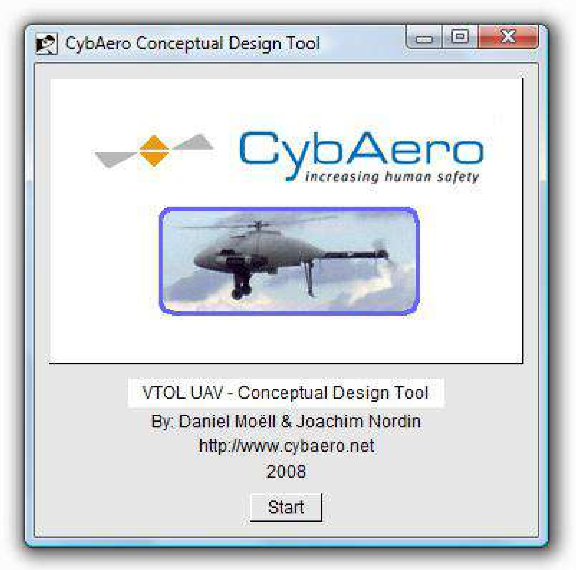

Fig. 4 Program start

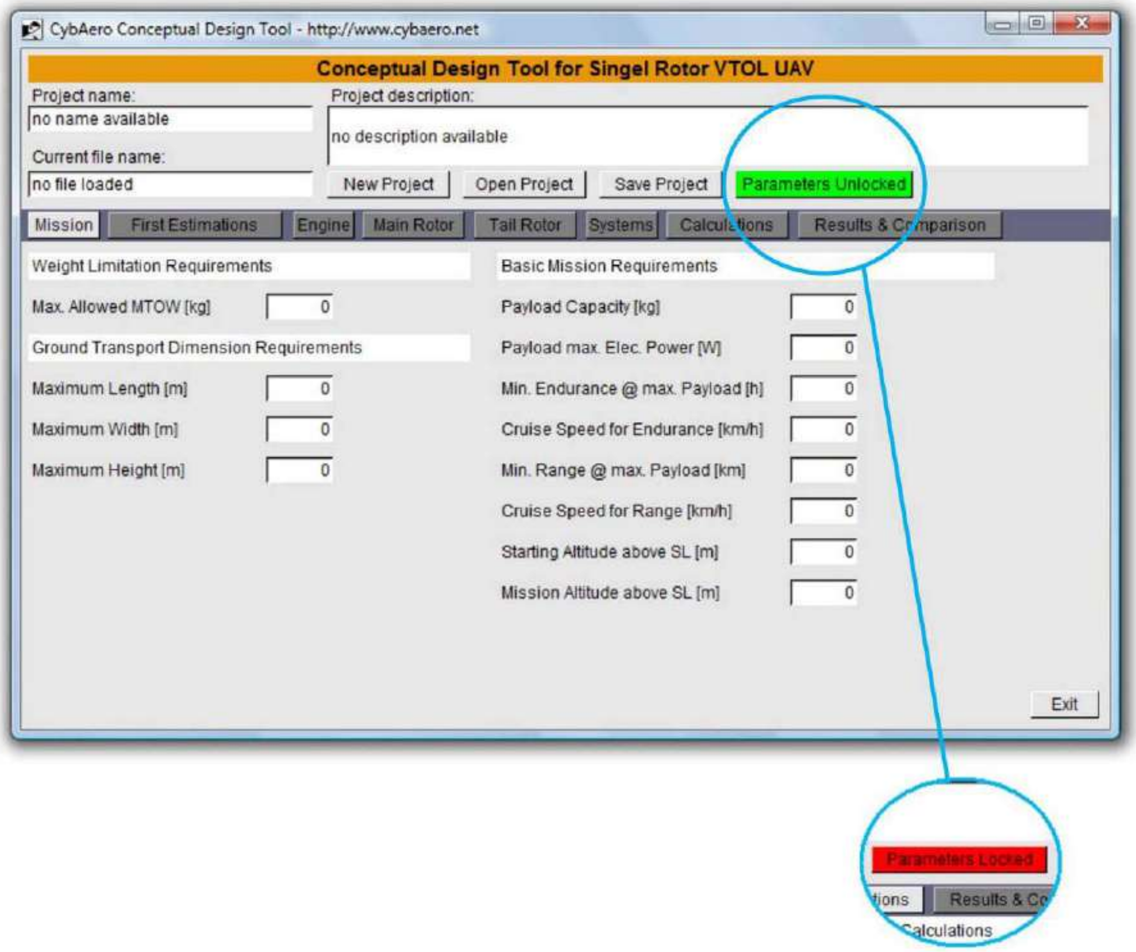

Fig. 5 Mission tab

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 fulfils 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.

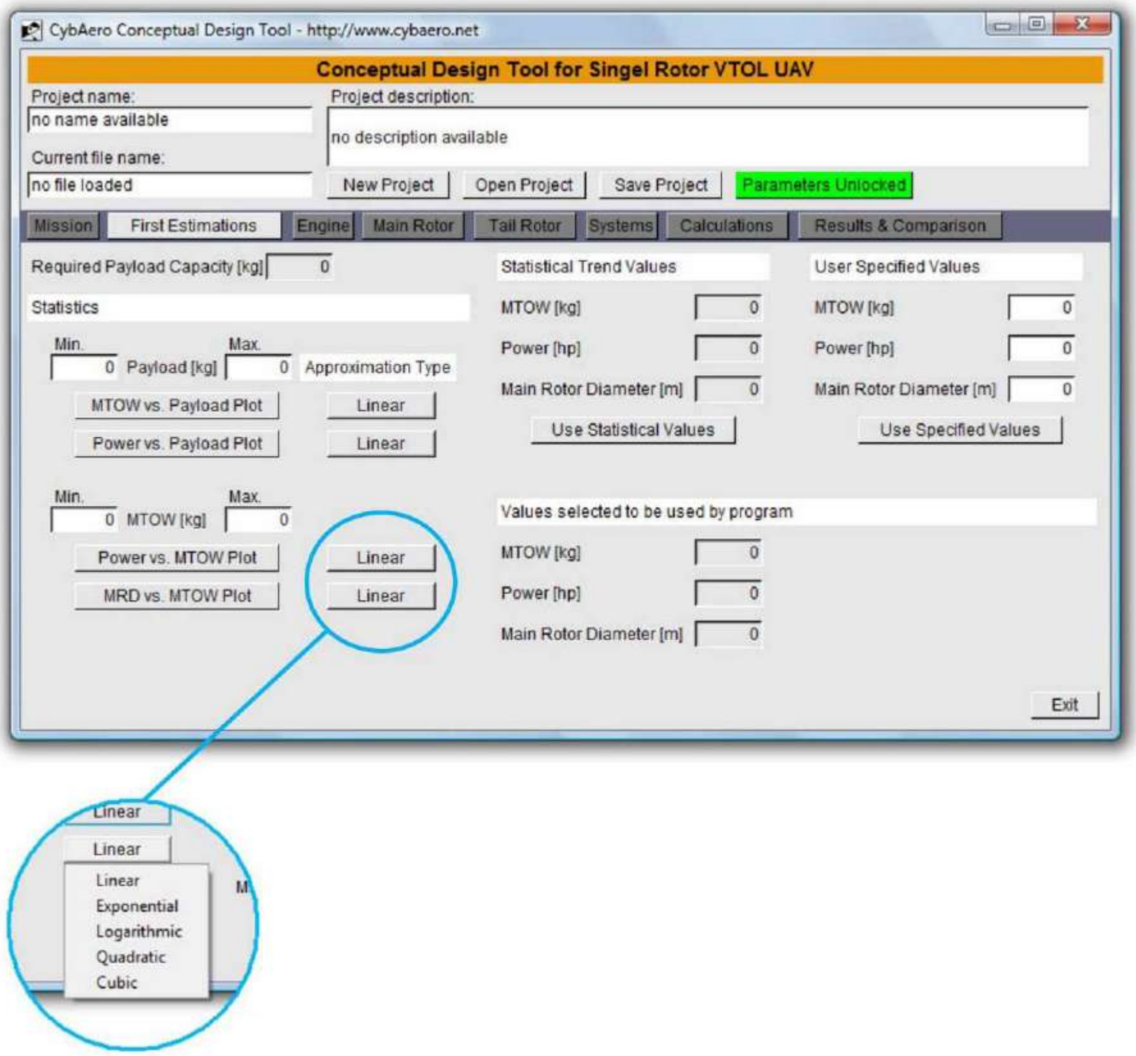

Fig. 6 First Estimations tab

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.

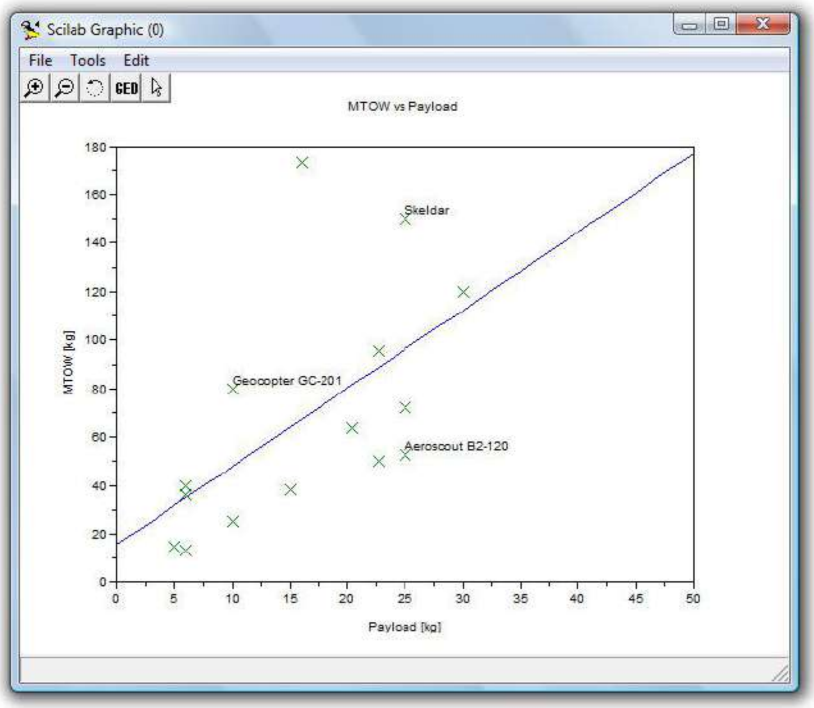

Fig. 7 Example plot of MTOW versus payload

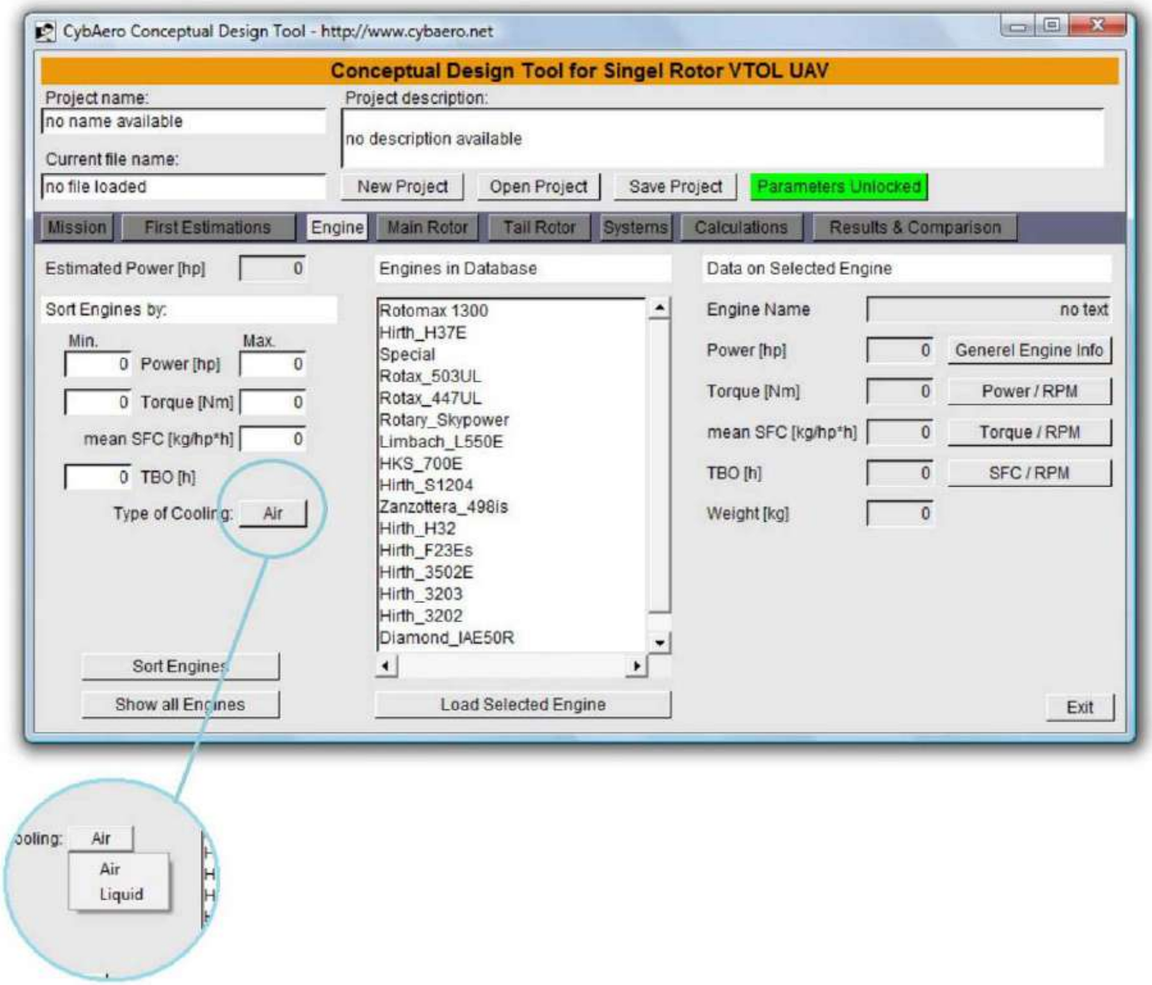

Fig. 8 Engine tab

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.

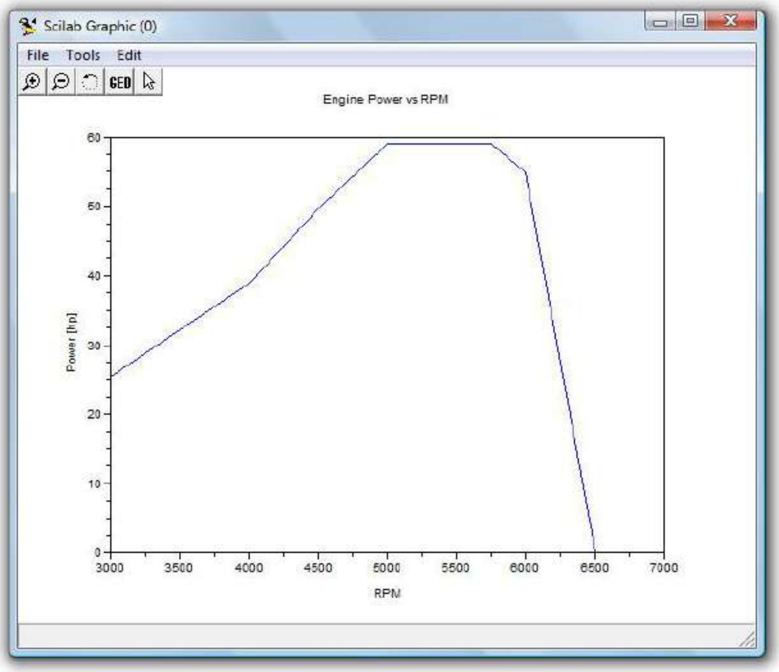

Fig. 9 Example plot of engine power versus rpm

Fig. 10 General engine info

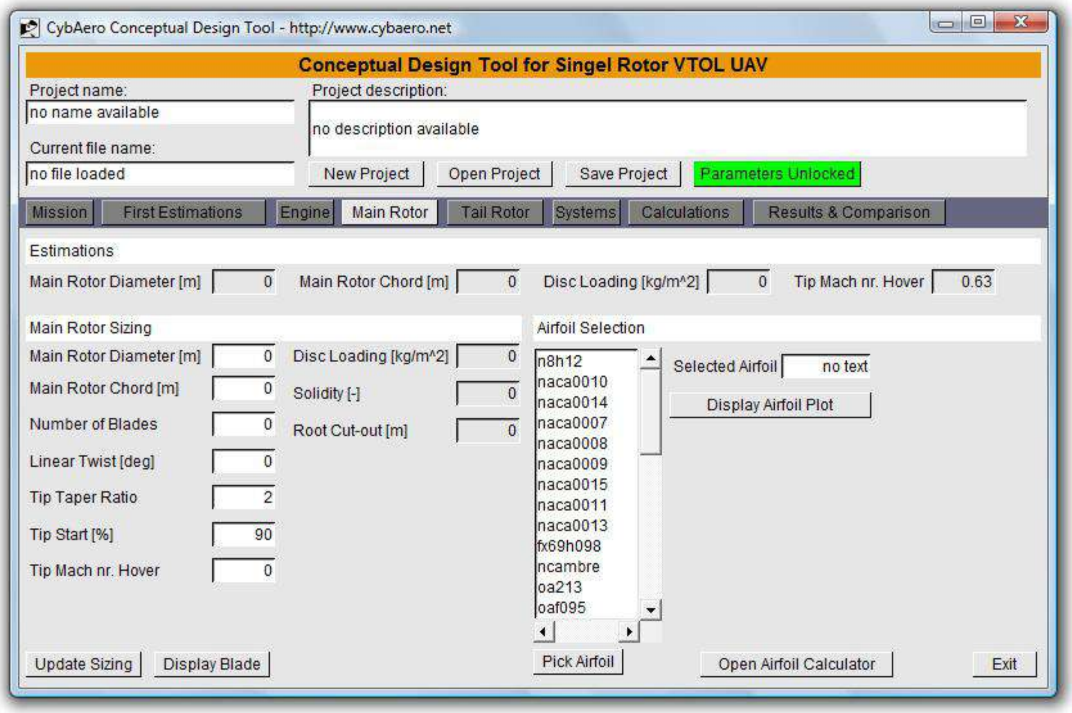

Fig. 11 Main Rotor tab

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.

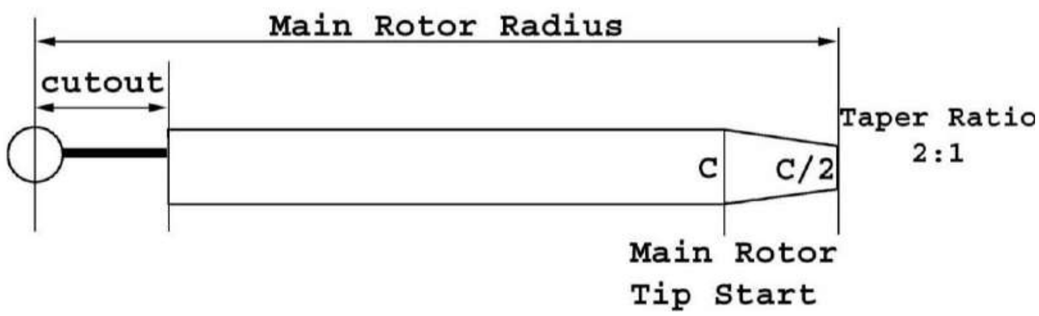

Fig. 12 Sketch of a main rotor blade

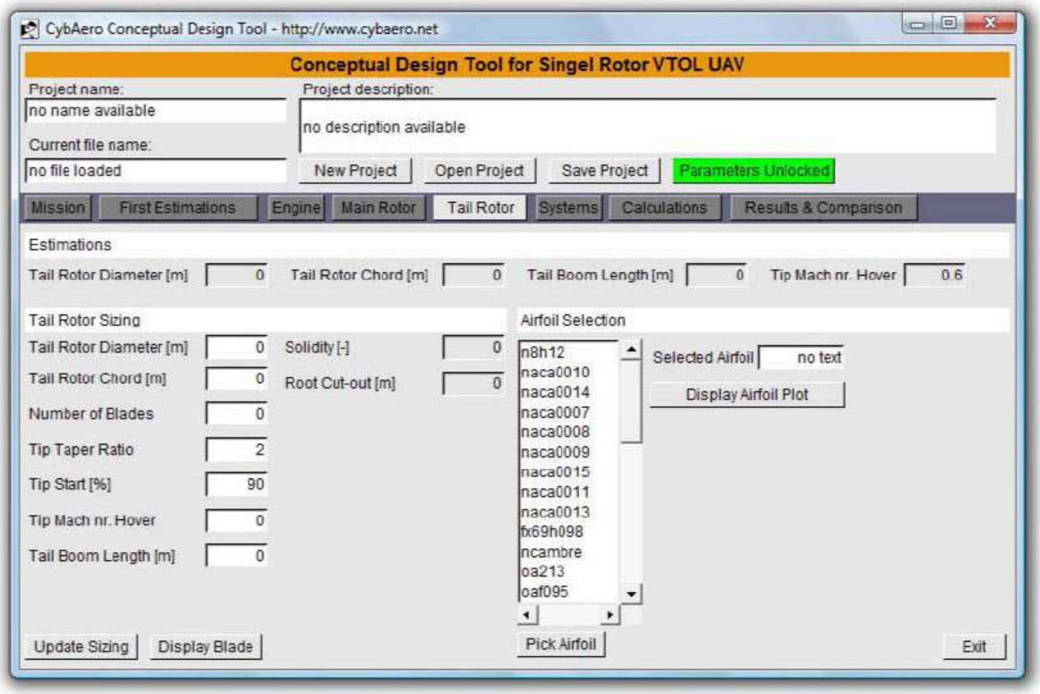

Fig. 13 Tail Rotor tab

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. 14.

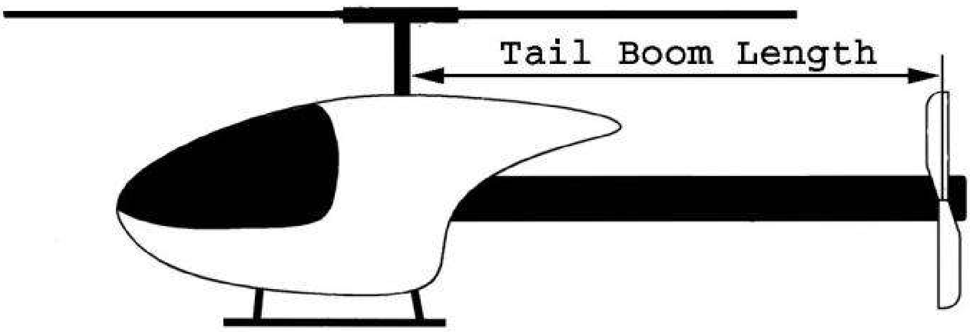

Fig. 14 Definition of the parameter “Tail Boom Length”

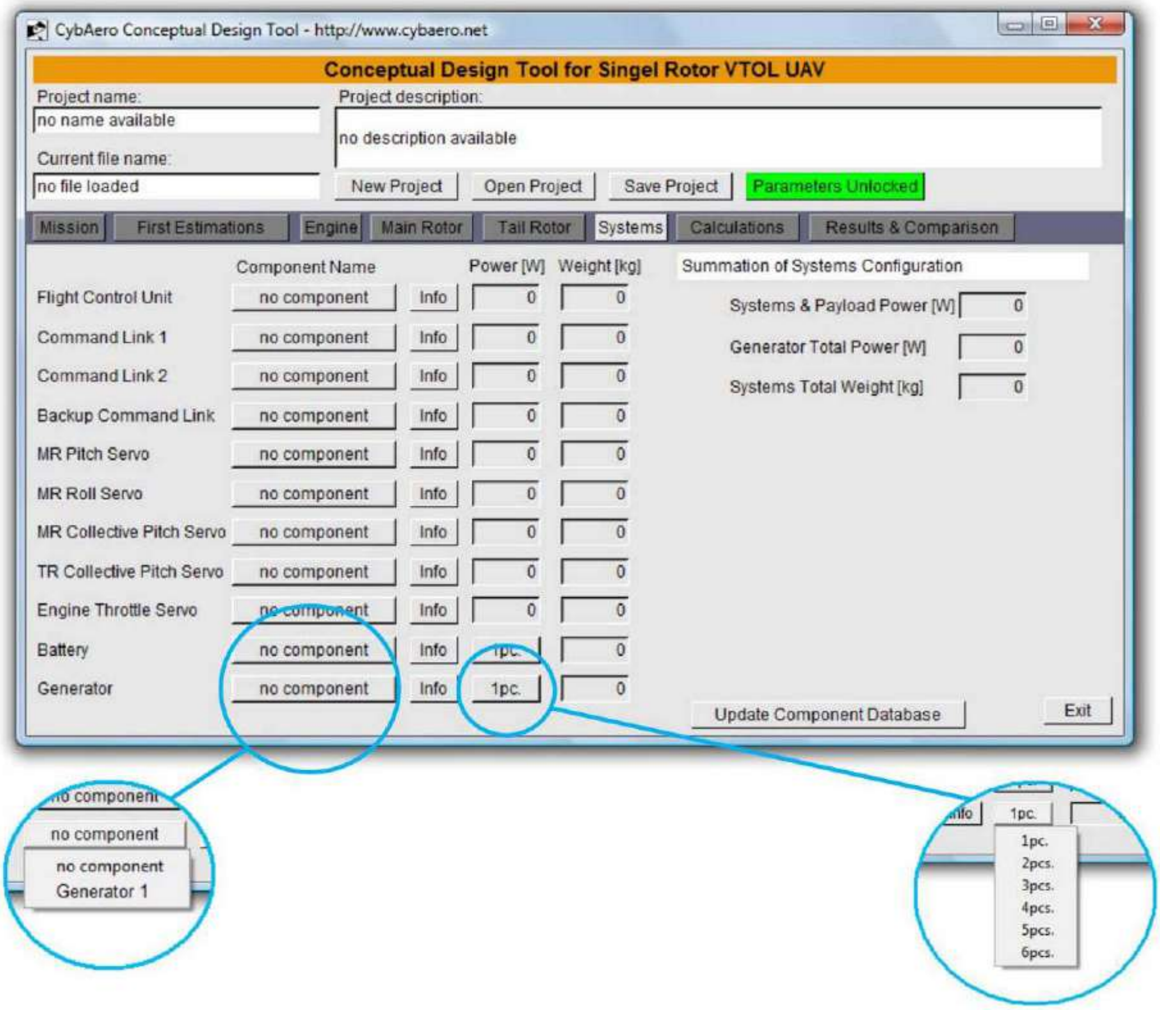

Fig. 15 Systems tab

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.

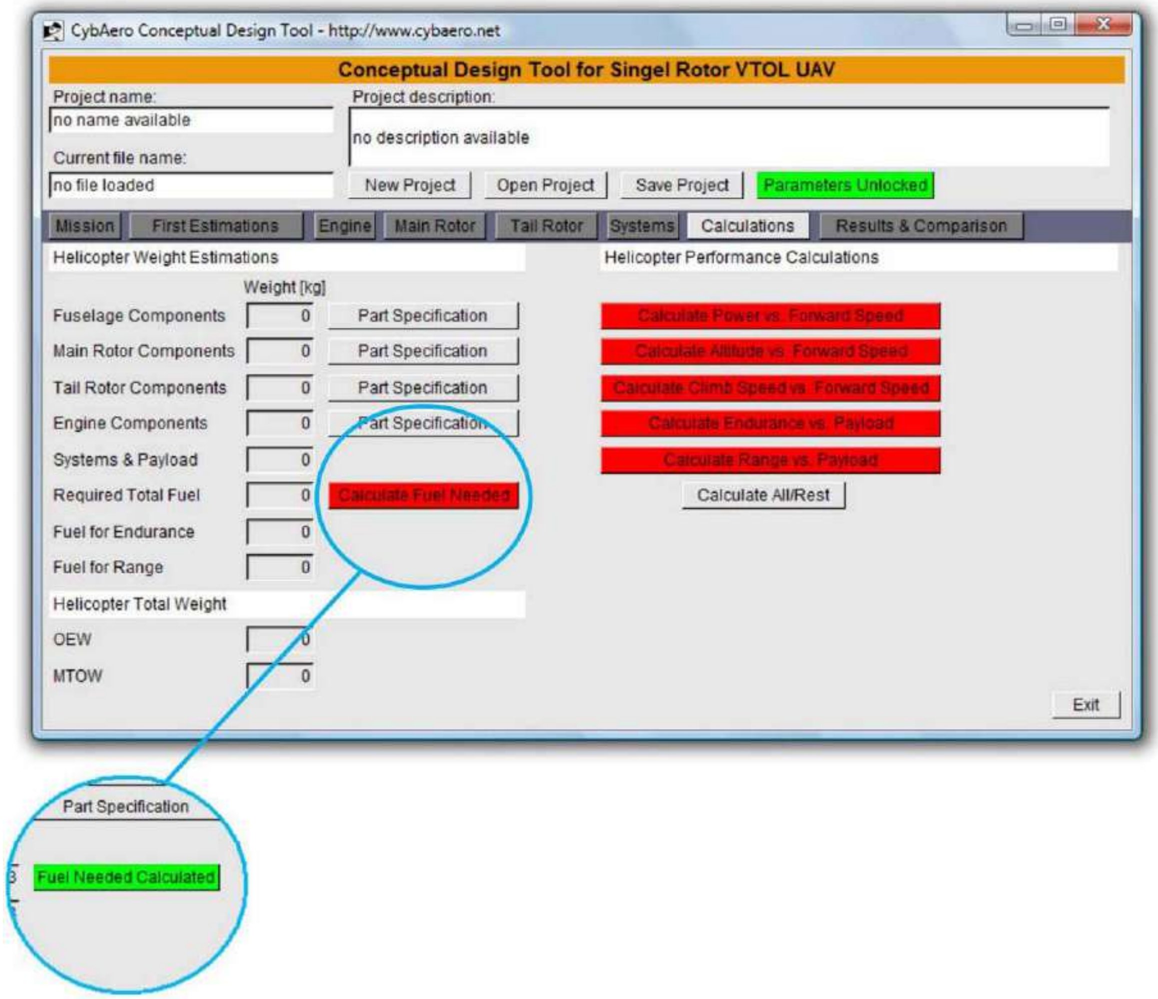

Fig. 16 Calculations tab

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.

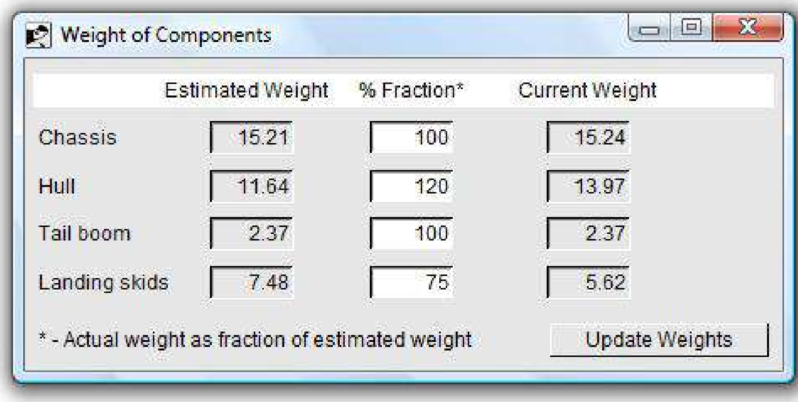

Fig. 17 Window showing the subparts of the fuselage

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.

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. 16. 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.

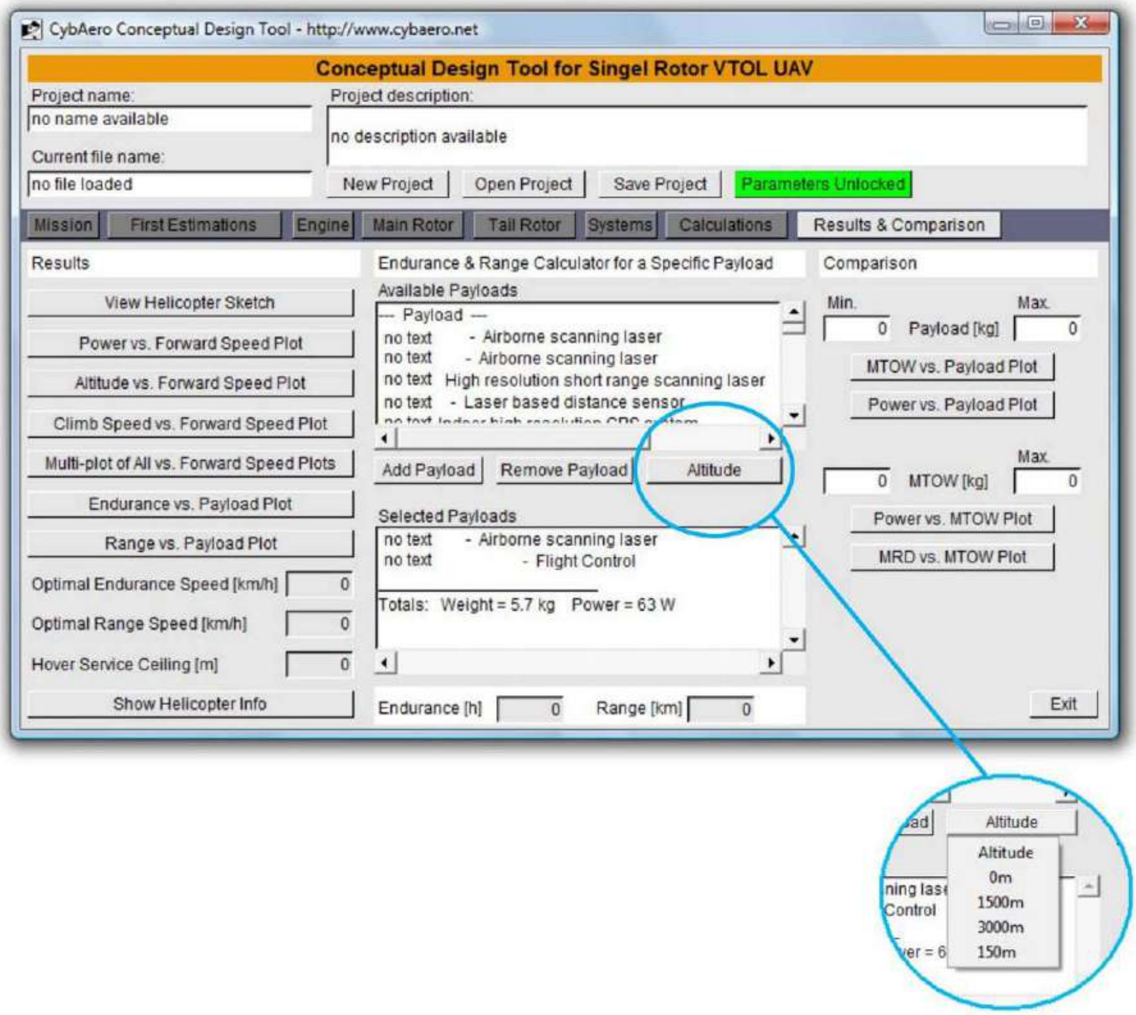

Fig. 18 Results & Comparison tab

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.

12. 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.

13. 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.

14. 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.

15. 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:

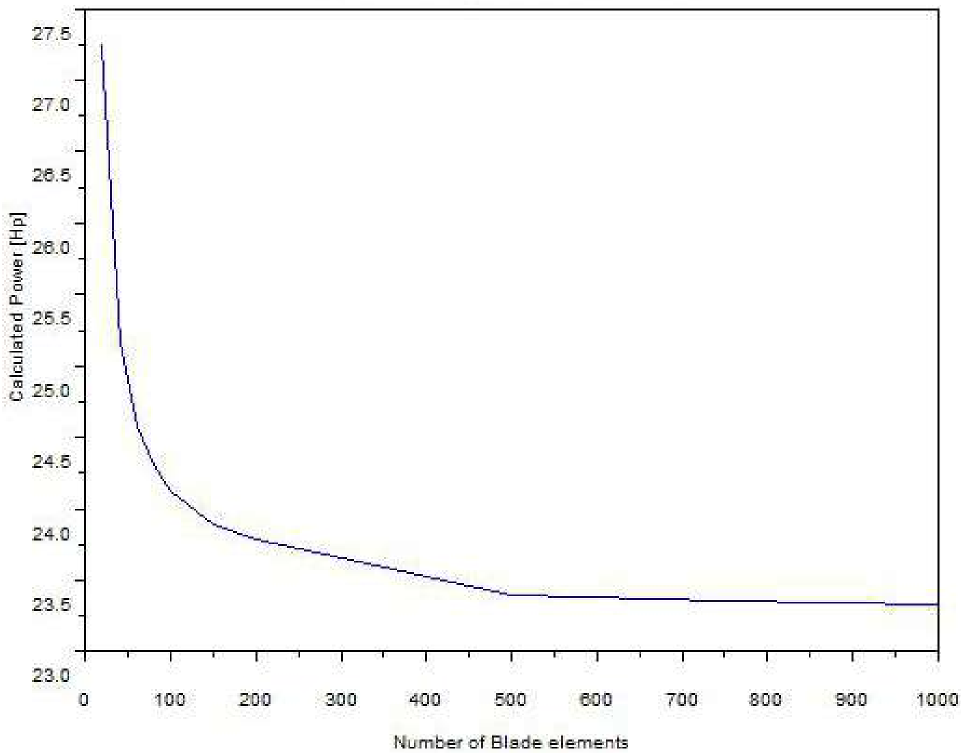

Fig. 19 Calculated power versus number of blade elements

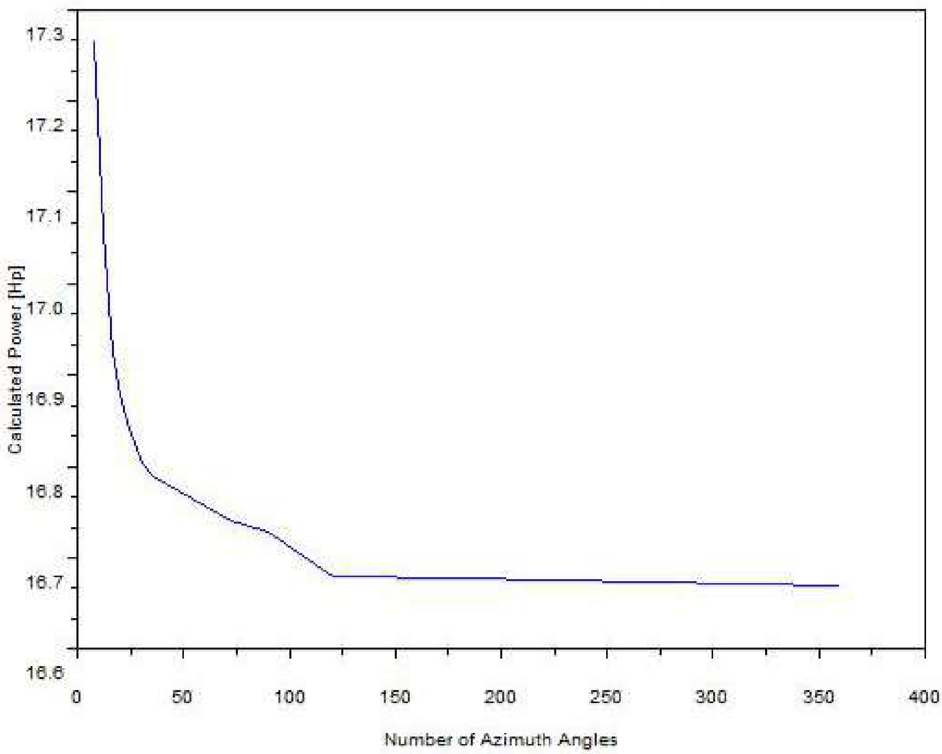

Fig. 20 Calculated power versus number of Azimuth positions

As shown in Figures 19 and 20 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:

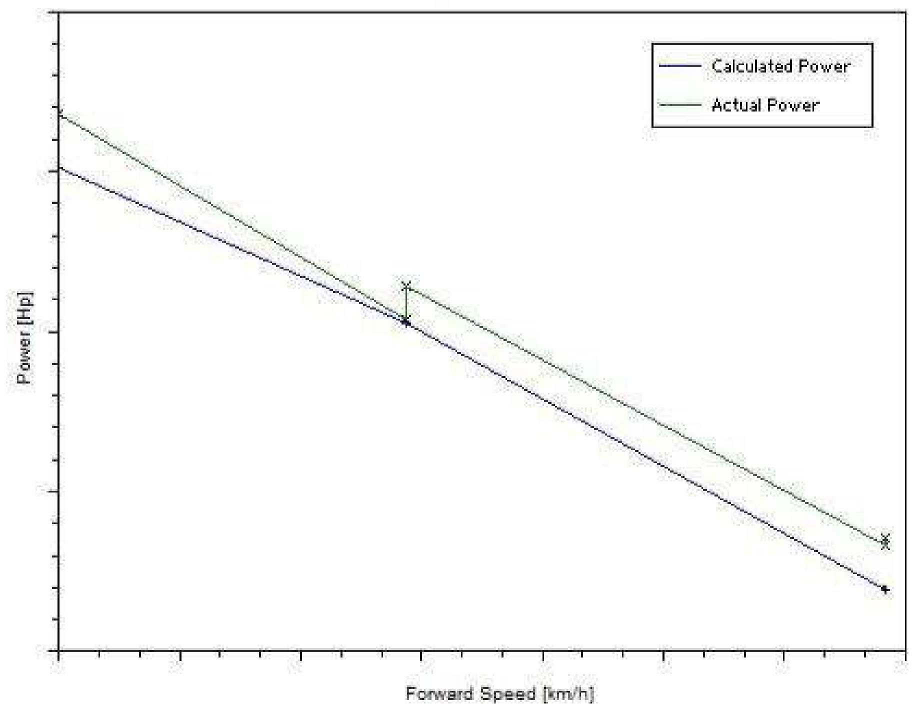

Fig. 21 Calculated power and actual power at forward flight

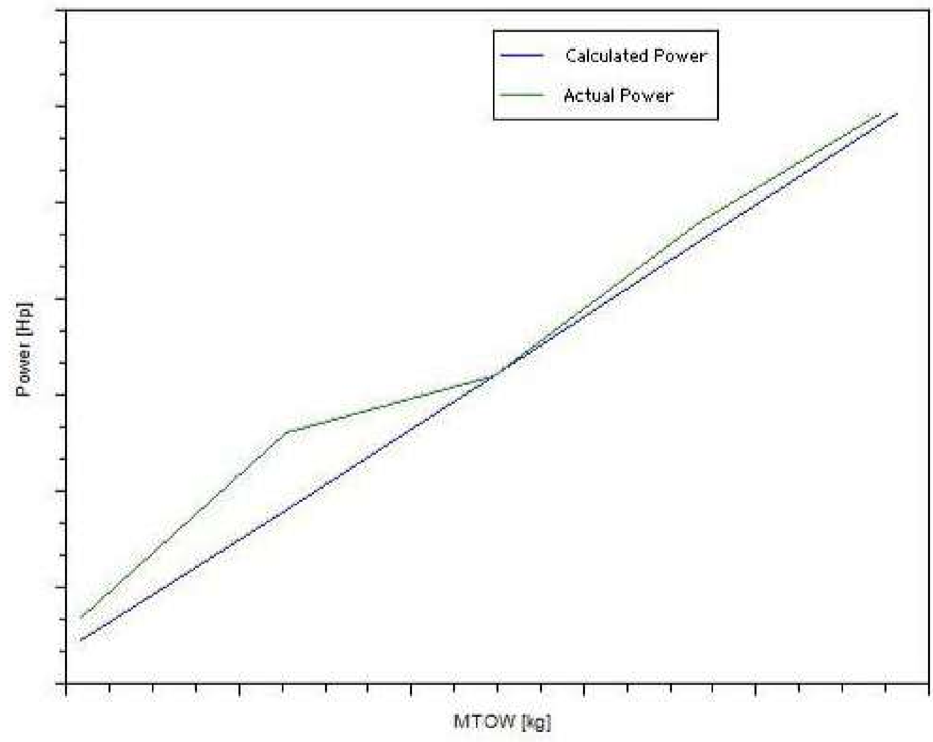

Fig. 22 Calculated power and actual power at hover

The power versus forward speed comparison in Figure 21 is in the speed range before the "turning point" of a general power curve like the one in Figure 23.

In Figures 21 and 22 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.

16. 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.

17. Output from the Design Tool

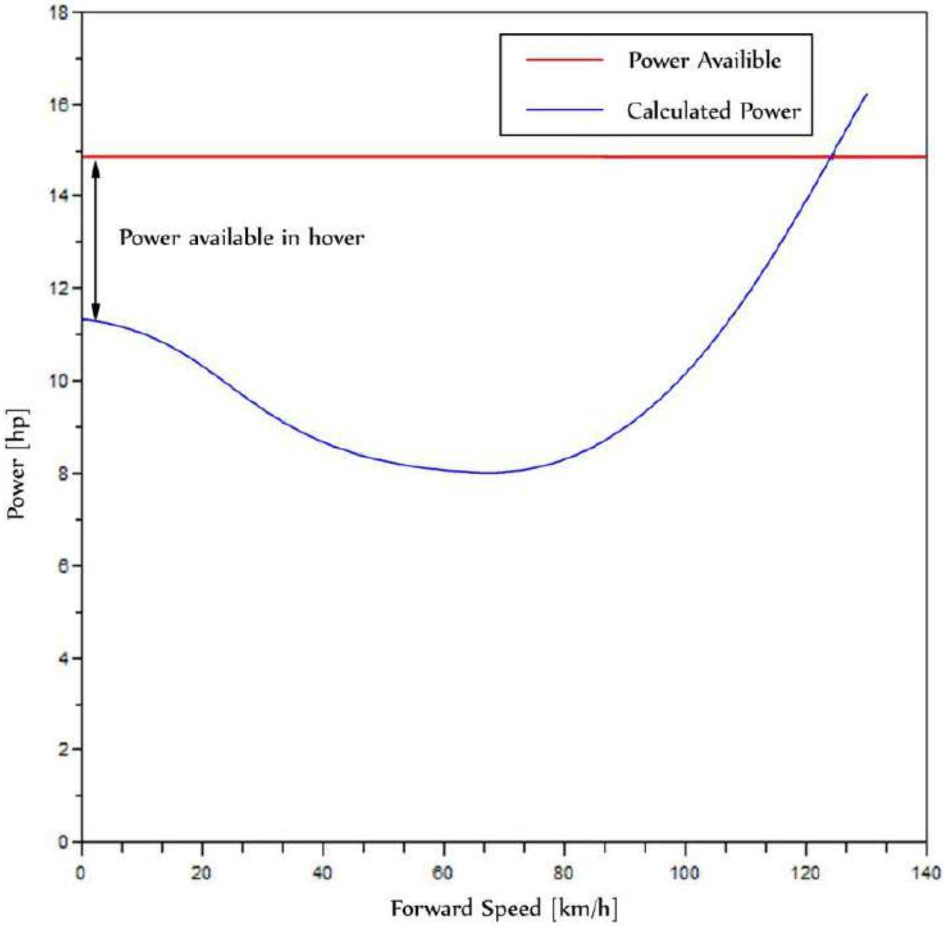

Fig. 23 Power versus forward speed

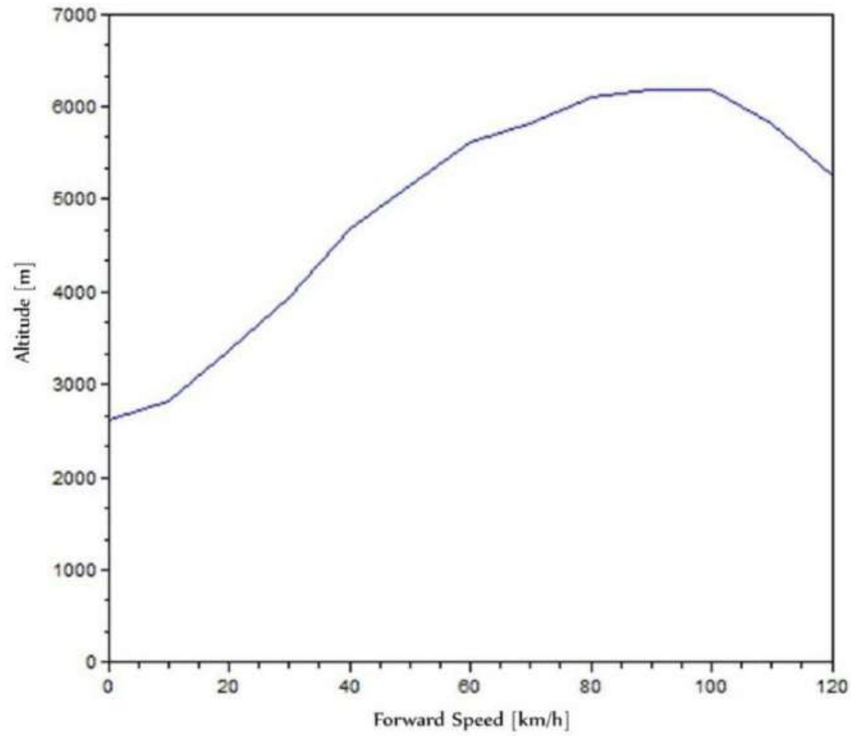

Fig. 24 Altitude versus forward speed

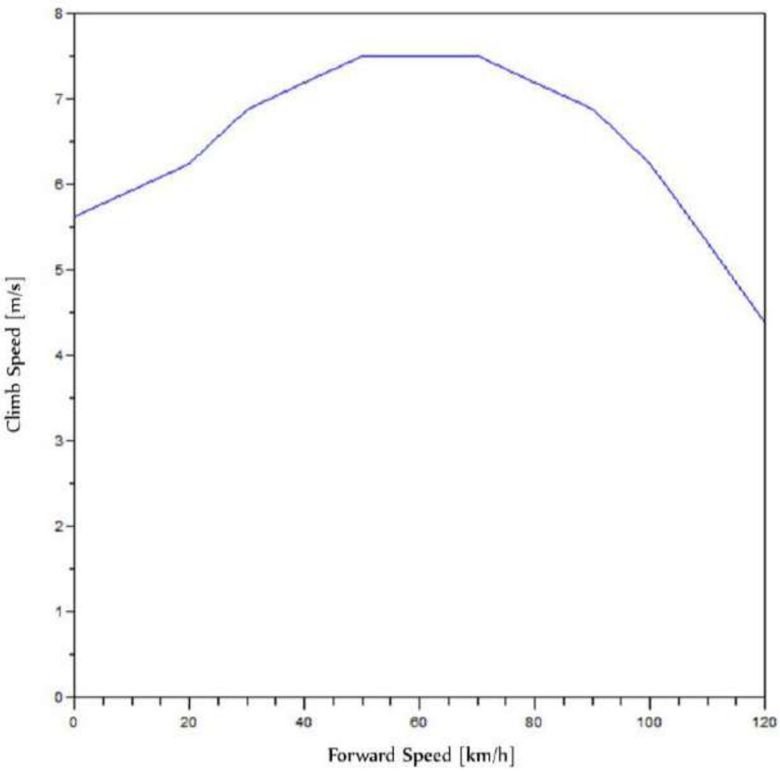

Fig. 25 Climb speed versus forward speed

In Figures 23, 24 and 25 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.

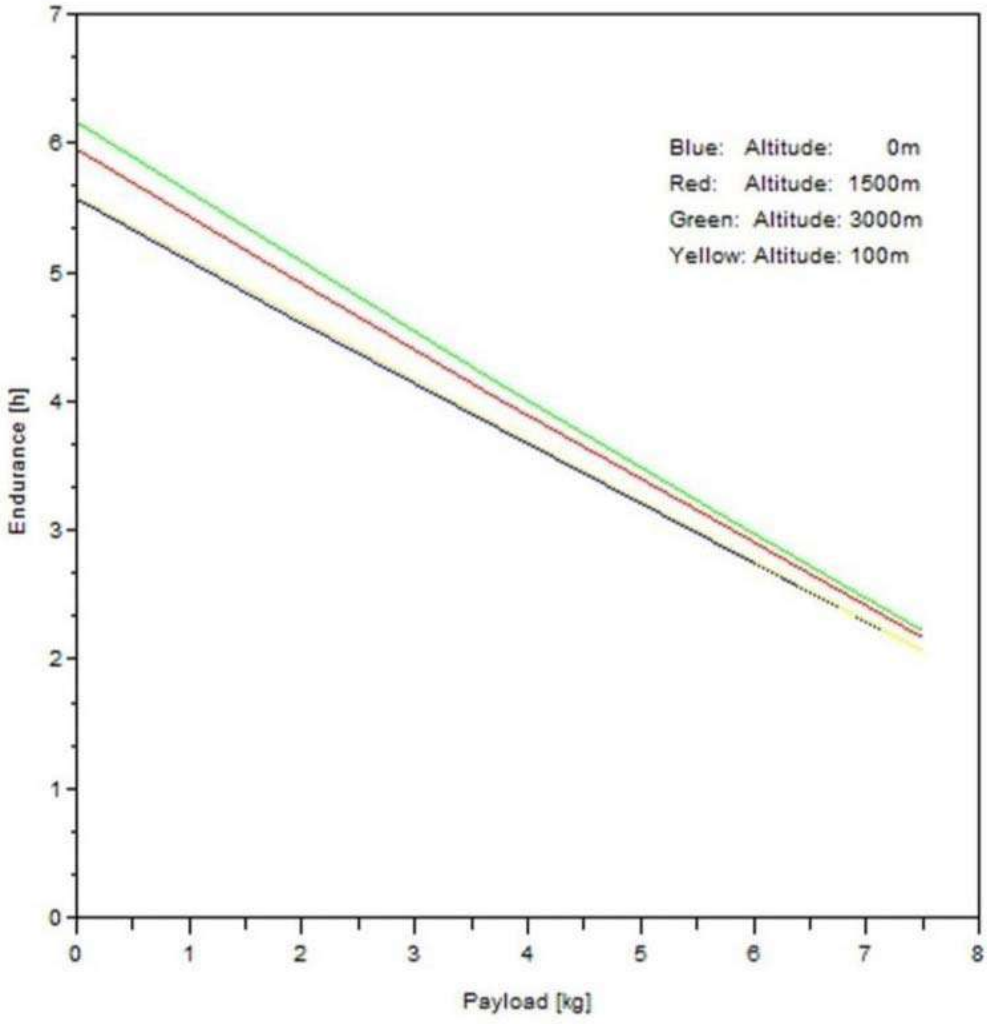

Fig. 26 Endurance versus payload

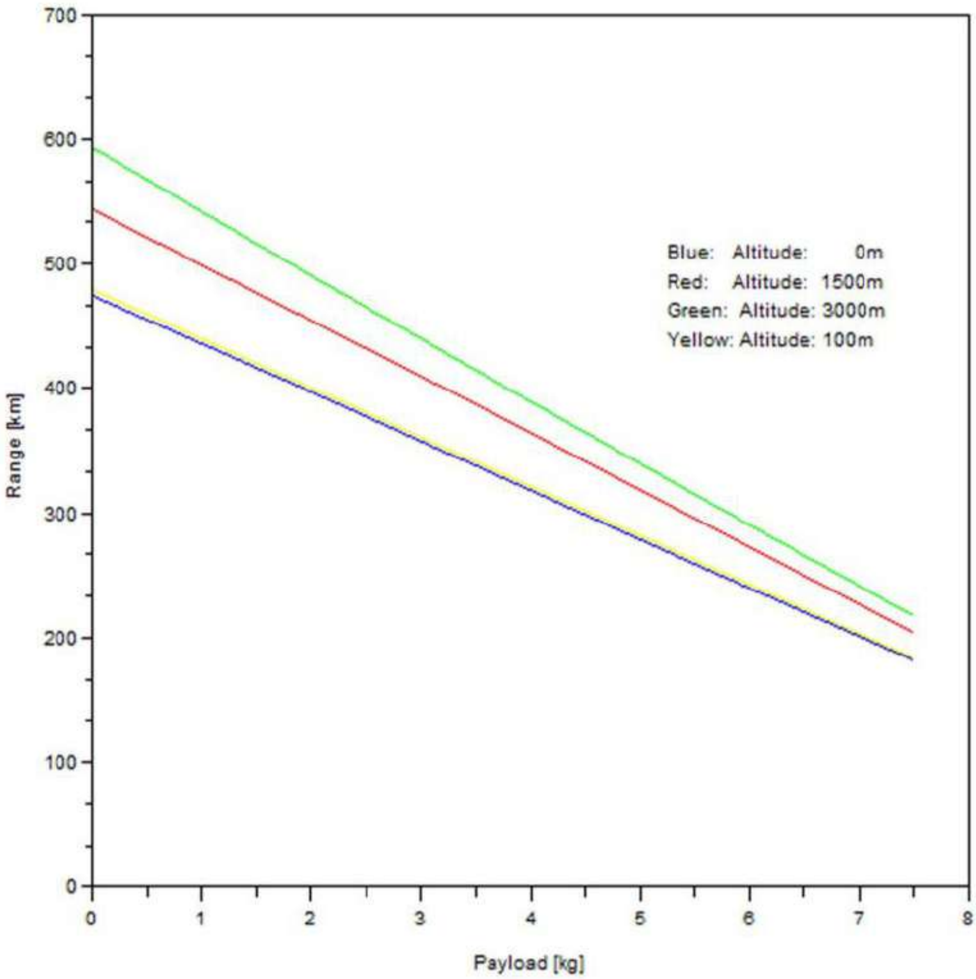

Fig. 27 Range versus payload

The results in Figures 26 and 27 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.

18. Conclusions

The outline of this paper 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 modelled 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 fulfils 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.

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