CERBERUS UCAV: Unmanned Combat Aerial Vehicle.

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Abstract

The "CERBERUS" is a unique vehicle with low RCS (Radar Cross Section) ,capable of performing missions in a range of 1000 [NM] with aerial-refueling capability after 1500 [NM], meaning that the aircraft can operate at a distance up to 1500 [NM] without refueling.

This vehicle is well equipped, carrying two smart bombs weighing 500 [kg] each. In addition it has an EO/IR (Electro-Optical and Infra Red) sensor and SAR for target detection ability during day and night at any weather condition. In order to communicate with the "CERBERUS" it has a Beyond LOS (Line of Sight) comm. capability.

During the work process a UCAV configuration survey was conducted and two configurations were chosen for the conceptual and preliminary design. After comparison of the configurations the optimal one was chosen.

A wind tunnel model test and a detailed design were conducted on the chosen configuration to insure that the theoretical calculations and design are valid.

Requirements and mission profile

- Operation range of 2000 NM with refueling capability
- Armament carrying capability of 2x500[kg] smart bombs
- Beyond LOS (Line of Sight) comm. capability
- Stealth capability
- Capability of carrying EO/IR sensors operating in all weather conditions, including night time target acquisition

Mission profile:

1) Taxi to runway
2) Warm-up
3) Takeoff
4) Climb to 36,000 ft
5) Cruise @ M=0.8 for 1,000 nm
6) 20 min loiter over target
7) Cruise @ M=0.8 for 500 nm
8) 10 min loiter for aerial refuel
9) Descend to S-L
10) Landing and taxi

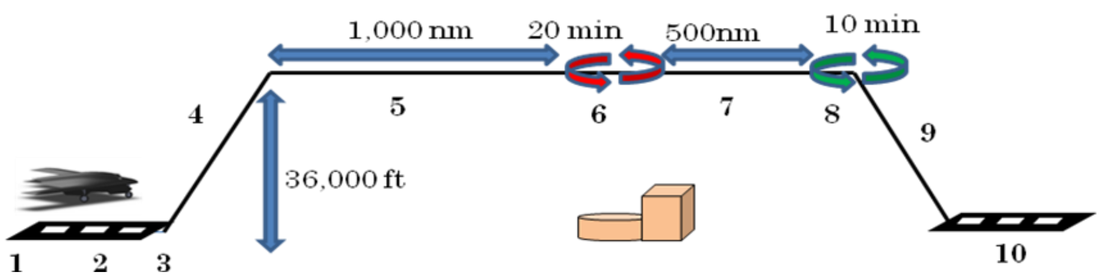

Figure1 : Mission Profile

In order to determine the overall shape and characteristics of the aircraft, a UCAV survey was conducted regarding all existing UCAVs that fit our mission requirements. It was clearly noticed that all UCAVs with low RCS were designed as a flying wing configuration (i.e. no definite fuselage) therefore it was decided that the Cerberus also be designed that way.

Two different flying wing configurations were suggested: delta wing and a lambda (zig-zag) wing.

Figure 2: Delta wing (left) and lambda (right)

Conceptual design

During the conceptual design stage we performed a full survey regarding avionics subsystems such as: SAR, EO/IR sensor for target acquisition and detection, satellite communication, GPS/INS module, IFF transponder etc. Finally components were selected that meet our requirements. Also an armament survey was conducted to find the most suitable armament to fit inside the UCAV. Due to RCS requirements all armaments are to be placed in specially designed compartments therefore it was important to find the smallest bomb possible.

We performed an RCS study to determine the overall shape of the Cerberus. It was shown that in order to reduce RCS the UCAV should be designed without a vertical stabilizer, meaning that wing control surfaces act as both elevators and ailerons. Also in order to obtain yaw control it was suggested that we use forward opening spoilers located on top of the wing. Since little is known about this method, it will be tested during a wind tunnel test.

Next we performed an initial sizing process on both configurations to determine takeoff weight and required fuel and thrust for the mission. We also examined the differences between single and twin engine configurations and concluded that the single engine configuration is more suitable as it is lighter and requires less fuel. Once the single engine configuration was chosen, an engines survey was conducted to find the most suitable engine to accommodate the mission requirements.

The selected engine is: **P&W pw306Aa**

Thrust:6400 [lb st]
Weight: 1043 [lb]
Fan diameter: 31.6 [in]
TSFC min:0.394 [lb/hr/lb]

Lastly, an airfoil survey was performed to locate the best airfoil for our mission. Since flying wings are known to be longitudinally unstable, due the lack of a vertical tail, we seeked an airfoil that would provide us with sufficient stability margin. The chosen airfoil is the Eppler 360 reflex airfoil. Its C.P is located further from the leading edge than normal airfoils which gives us more leeway in locating the C.G of the aircraft.

Preliminary design

The next stage was to perform the preliminary design on both configurations.

We conducted a system arrangement in order to determine if the available volume in both configurations is sufficient for all of the avionics, required fuel and armaments.

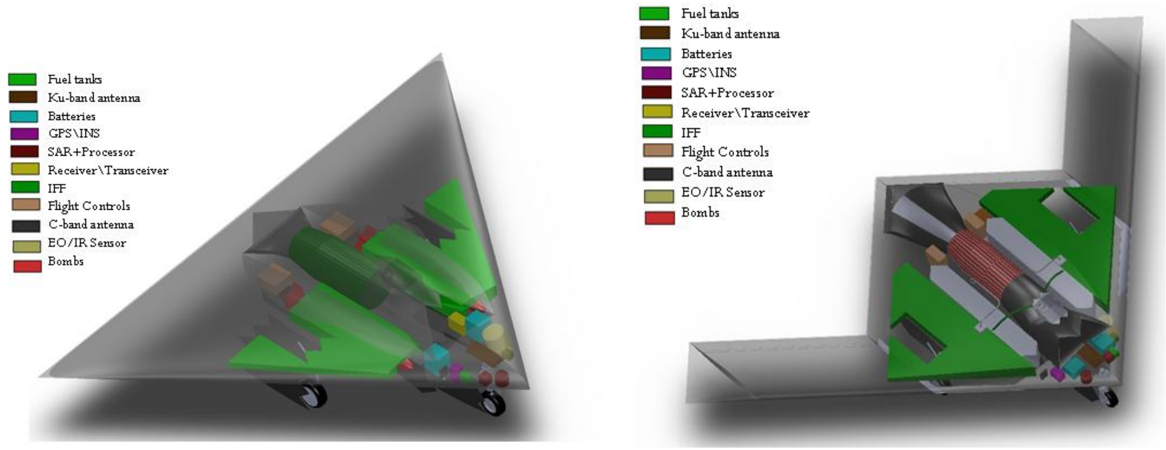

Figure 3: Layout of both configurations

Next we determined the landing gear arrangement and location. It was decided that we use the tricycle configuration as it allows for easier landings. Wheel span and size were then calculated to satisfy taxi and landing requirements.

Since our mission calls for an aerial refueling stage, it was needed to select an aerial refueling technique. We chose the boom and receptacle method due to its lower complexity during the refueling process and its smaller effect on the aircrafts RCS.

Next we designed the engine's air inlet and tailpipe. The goal was to minimize radar returns from the intake as much as possible by curving it to an S shape, while maintaining inlet efficiency. The tailpipe had to be designed to minimize IR signature by mixing the hot air leaving the engine with the cold air outside as quickly as possible.

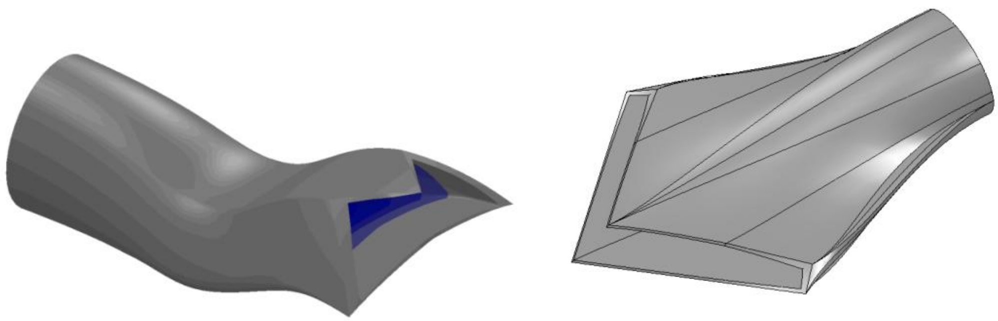

Figure 4: Inlet and tailpipe

Next we determined the required control surfaces size to allow for effective control. Since the mission does not call for sharp maneuvers, we focused on takeoff requirements (i.e. making sure that elevons can produce enough pitching moment to allow for takeoff within the required field length). After performing the necessary calculations, the required elevator deflection to allow takeoff was determined for both configurations.

After the preliminary design was finished we conducted performance calculations on both configurations. We examined takeoff and landing distance, climb rate at various heights, maximum range, required fuel etc. The results are summarized in the following table:

Parameter	**Lambda**	**Delta**
Weight	14,300 [lb]	14,460 [lb]
Fuel weight	3,117 [lb]	3,600 [lb]
Aspect Ratio	4.1	3
Wing loading	30 [lbf/ft^2]	36 [lbf/ft^2]
Engine	P&W pw306A	P&W pw306A
Airfoil	Eppler 360	Eppler 360
Flight ceiling	46,000 [ft]	40,000 [ft]
Takeoff distance	1.22 [km]	1.15 [km]
Takeoff rotation (elevon angle)	13.9°	5.7°
Landing distance	1.19 [km]	1.03 [km]
Aerial refueling time	35 [sec]	40 [sec]
Climb rate (36,000 [ft])	4869 [ft/min]	4606 [ft/min]
Longitudinal stability	Unstable	Stable
No. of reflecting surfaces (RCS)	2	3

Table 1: Configuration comparison

As seen from the above table, both configurations have very similar characteristics, while at some parameters the lambda configuration is superior, and at others the delta configuration is better.
However there are some key parameters that enable us to choose one over the other: required fuel, aerodynamic efficiency and RCS.

We decided that the selected configuration is the lambda configuration. There are some parameters at which the delta configuration was better such as stability and takeoff rotation, but these problems are still within reasonable boundaries and can be handled by proper care and design.

From here on, the focus is on the detailed design of the lambda configuration only.

Detailed design

Once the configuration was selected we could re-design the systems arrangement in more detail. Since preliminary study showed that the lambda configuration is currently unstable we wanted to "pull" the C.G to the front of the aircraft in order to achieve stability. The systems final arrangement is as follows:

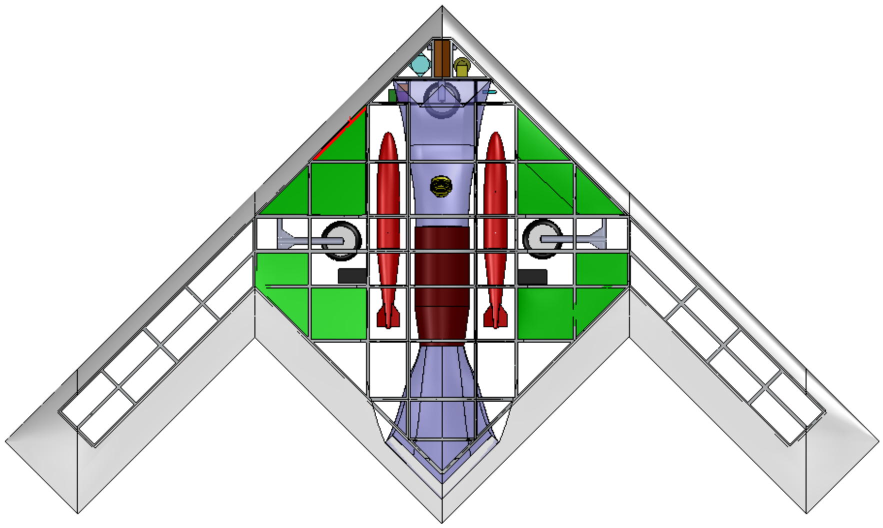

Figure 5: System arrangement

We can clearly see that there is a lot of unused space in the aircraft's main body and in the wings; this space can be later used for accommodating more fuel to increase range or for installing more future systems which will upgrade the aircraft.

Structural design:

Since the aircraft is subjected to various loads during flight, it was important to design the structure in such a way as to withstand those loads without failing, while keeping the weight as low as possible. We decided to use an I cross section beam due to its high moment of inertia and low weight. The material selected was an aluminum alloy. Also the structure must allow space for armaments, fuel, landing gears, engine and avionics. Changes were made in the landing gear design and the wheel span was increased to allow for easier retraction.

Below is the CAD representation of the structure:

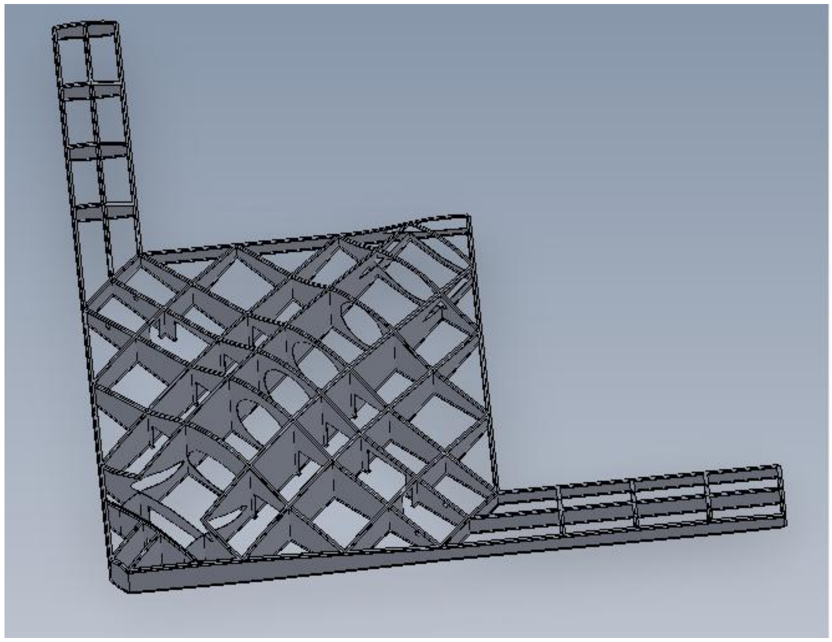

Figure 6: Structure

Structural analysis:

Once the aircrafts structure had been determined we could perform a structural analysis. We used the Ansys software which employs the finite element method. The aircraft was loaded with a lift force equal to twice its weight to simulate a 2g maneuver. However, to simplify calculations we performed the analysis on a section of the UCAV. The results are as follows:

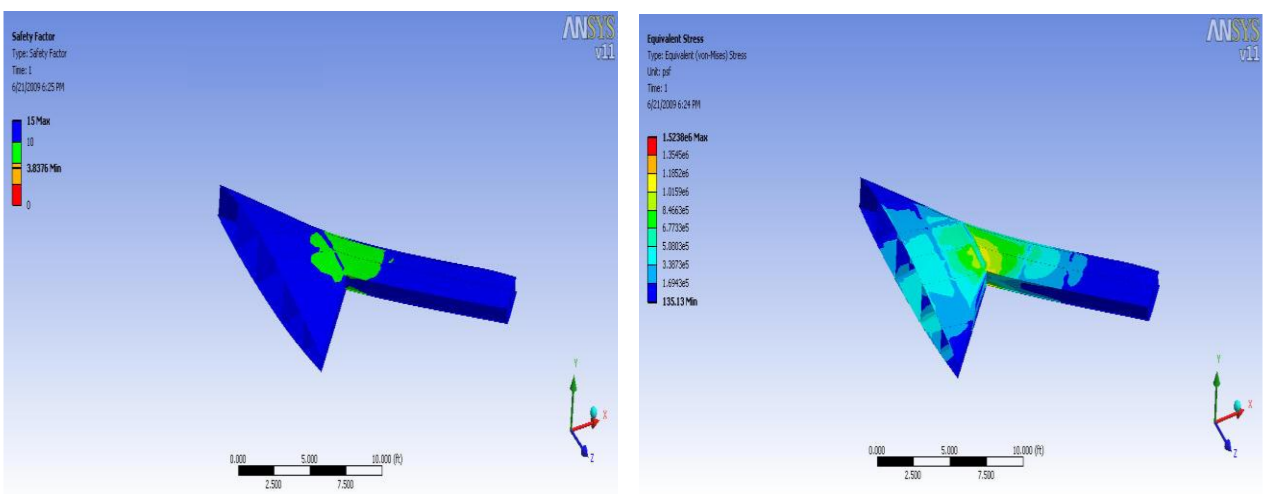

Figure7 : Ansys results (left: safety factor, right: VM stress)

It can be seen that the minimal safety factor is present in the connection between the outer and inner wing where the maximal stress is developed; the safety factor there equals to: 3.8376; the maximal safety factor in the structure is 15.

Both of these values are extremely high and unacceptable in the aviation industry, where safety factor values generally range between 1.1-1.2.

In order to reduce the safety factors, more iterations are needed, but were not done due to a lack of time.

It is obvious that the inner wing outer wing connection is the most vulnerable area of the UCAV, therefore a detailed design of that area was conducted. All beams and ribs were created using a CAD software then drilled with holes and connected to each other with bolts. The area was then loaded with the corresponding loads (forces and moments). The results are as follows:

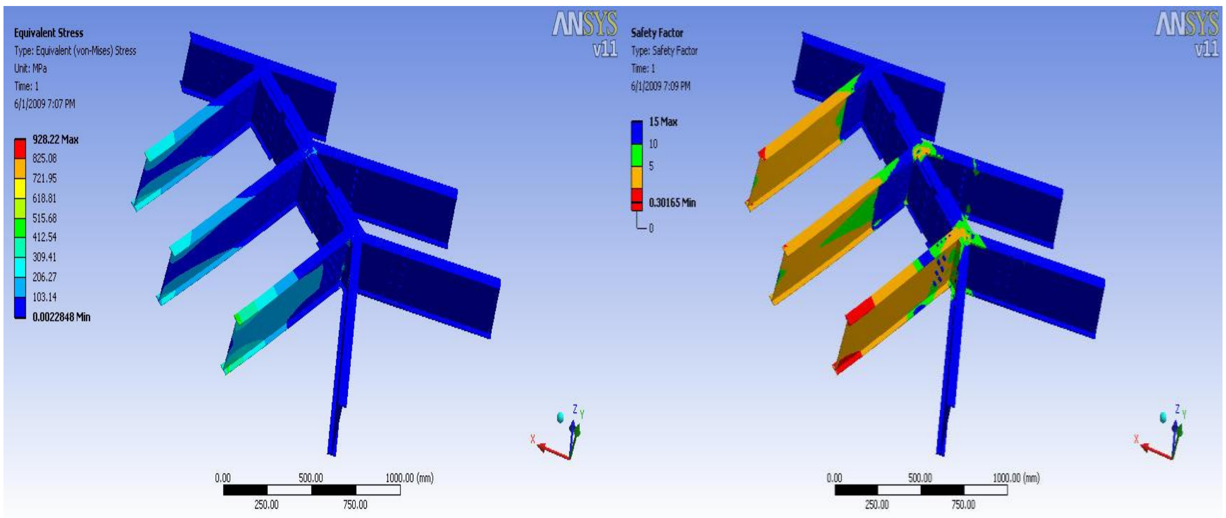

Figure 8: Beam connection Ansys results (left: VM stress, right: safety factor)

As expected the maximal stresses are located at the U connections, namely, at the trailing edge connection. The minimal safety factor, obtained at the root area is a result of the boundary condition set at that edge. In reality we can expect the safety to be significantly higher.

The actual minimal safety factor is approximately 3 which is still too high for aeronautical design.

It is obvious from the results that there is room for more design iterations in order to reduce the safety factor and consequently the weight.

RCS analysis:

RCS Computer model was created and analyzed using physical optical approximation method. Additionally, the same RCS analysis was conducted by “Rafael - advanced defense systems”. Eventually, the two analysis’ results were compared.

The RCS evaluation was conducted under two different frequencies: **1GHz** and **20GHz**.

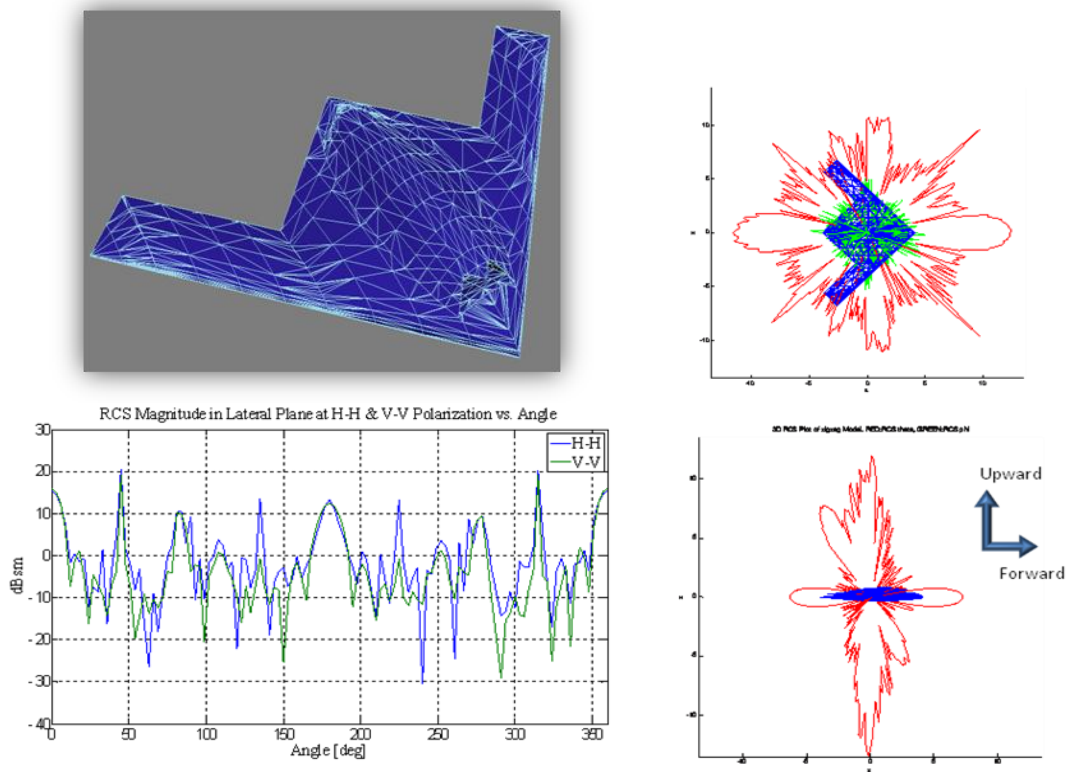

Figure 9: RCS analysis results

Above is the analysis results for a frequency of 1 GHz.

As expected, the largest diffractions correspond to the sweep angle and from the intake and outtake. Additional decrease in RCS can be achieved by using RAM coating.

Weight and balance analysis:

After several iterations of the systems' arrangements and structure, the final layout of the aircraft has been set and a new C.G. calculation could be made. The results are shown in the following table:

Component	Weight [lb]	Location [ft]
Structure	2867	13.8
Engine	1043	13.02
Air induct	177.3	7.44
Tailpipe	60.2	20.06
Nose landing gear	193.1	5.23
Main landing gear	851.6	11.85
Propulsion system	177.5	13.02
Fuel	3257.9	11.4
Aerial refuel	294.6	8.34
Hydraulics	171.7	13.02
Electrical system	113.6	3.47
Avionics	1159.5	3.47
Flight control	127.2	13.8
Armament	2205	10.54
Misc (spread)	779	11.05
Weight Reserve	816	11.05
Aft C.G.	14300	11.14
Forward C.G.		10.9

Table 2: C.G. calculation

Model design:

Two models were considered: subsonic and transonic. The transonic model better simulates flight conditions in terms of air density and velocity. However the transonic tunnel's cross section dictates that the max model's scale will be 1:35 which is drastically small. Size limitations led to a very fragile model and unrealistic geometry.

Therefore the subsonic model was constructed and results would be adjusted using the prandtl-glauert transformation.

Wind tunnel tests:

In order to proceed with the performance calculations and flight control design, a wind tunnel test had to be conducted to determine the stability derivatives and aerodynamic characteristics of the aircraft. First a wind tunnel model was designed then manufactured using a rapid prototyping method. The test was conducted at a subsonic tunnel due to its larger cross section area, and results were corrected using the prandtl-glauert transformation.

Along with the model, control surfaces such as elevons and spoilers at different angles were manufactured to establish the control surfaces effect on roll, yaw and pitch. A full testing plan was established and carried out, testing the aircraft's aerodynamic behavior in the presence of various angles of attack, slip angles and control surfaces angles. Some of the results are shown below:

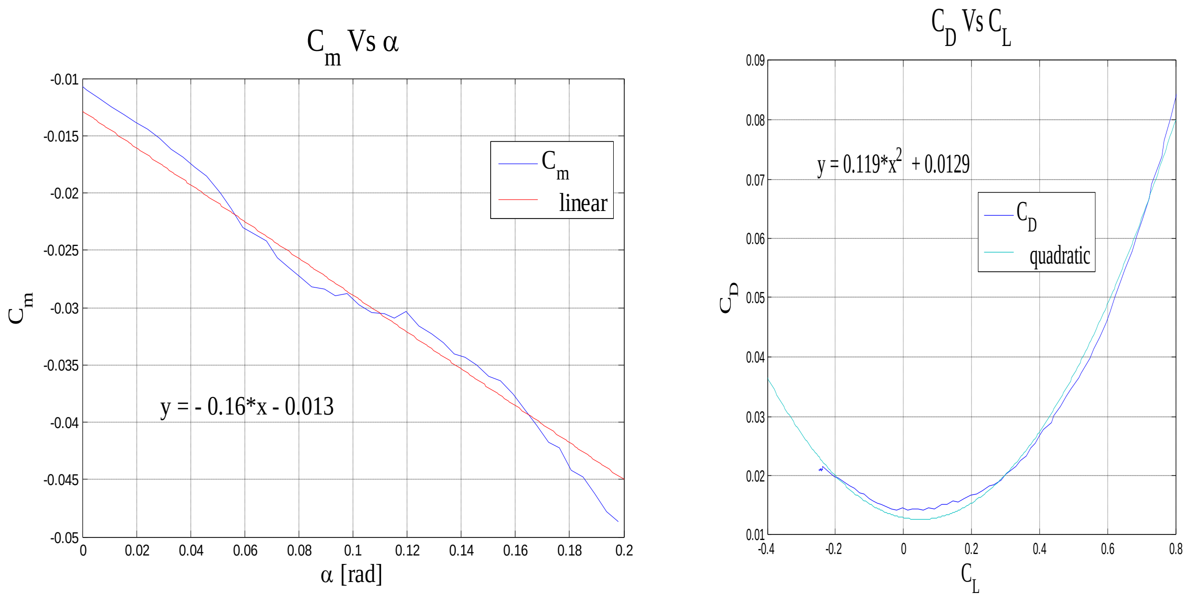

Figure 10: Wind tunnel test results – longitudinal plane

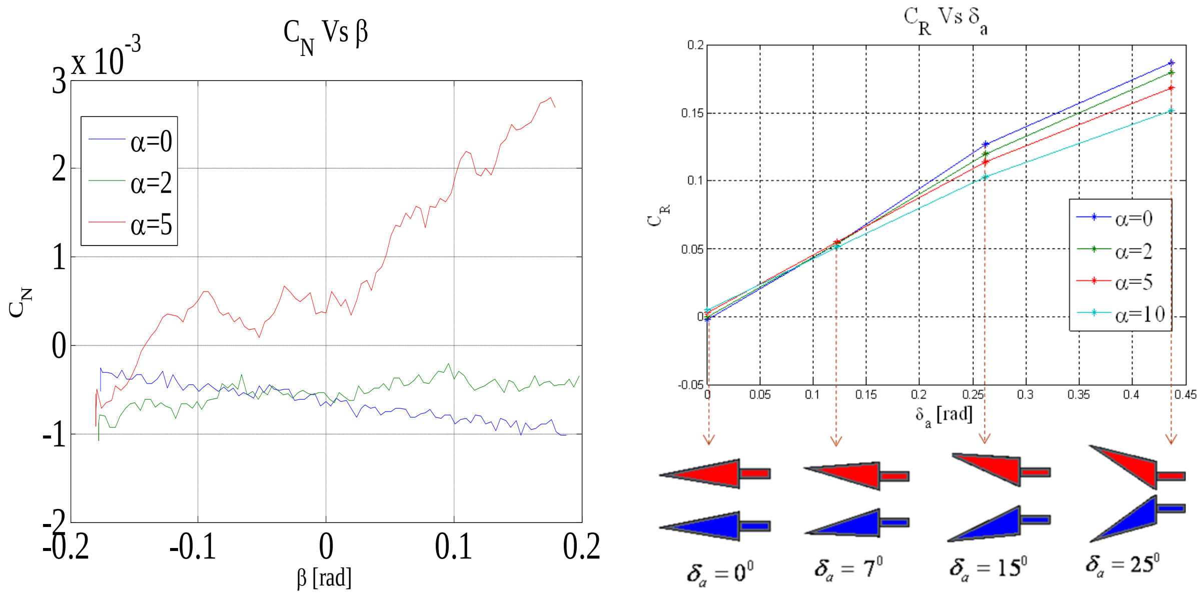

Figure 11: Wind tunnel test results - lateral plane

It can be seen now that contrary to preliminary assessments, the aircraft is longitudinally stable, making the design of the longitudinal control system far simpler. However due to the lack of a vertical stabilizer, weathercock stability is compromised at certain angles of attack, meaning that the aircraft will have to be stabilized by the control system.

Performance analysis:

Once test results had been analyzed and stability derivatives had been established, we could begin with the detailed performance analysis of the aircraft.

While performing the new calculations it was noticed that the aircraft's range had dropped, therefore two alternatives were suggested in order to complete the mission:

Option 1 – Cruise speed at mach 0.75 and at 40,000 ft altitude.

Using this option we receive an L/D value of 12.5 and to complete the mission range of 1500 NM an extra 1480 lbs of fuel is required.

Option 2 – Optimal cruise speed for range at mach 0.66 and at an altitude of 40,000 ft.

Using the second option we receive the optimal range L/D value of 13.36 and to complete the mission range of 1500 NM an extra 1180 lbs of fuel is required.

Both of these options are valid as there is enough weight reserve taken into consideration to allow for the extra fuel weight, as well as enough volume in the outer wings of the aircraft to store the extra fuel. Also we were now able to construct the updated flight envelope and V-N diagram:

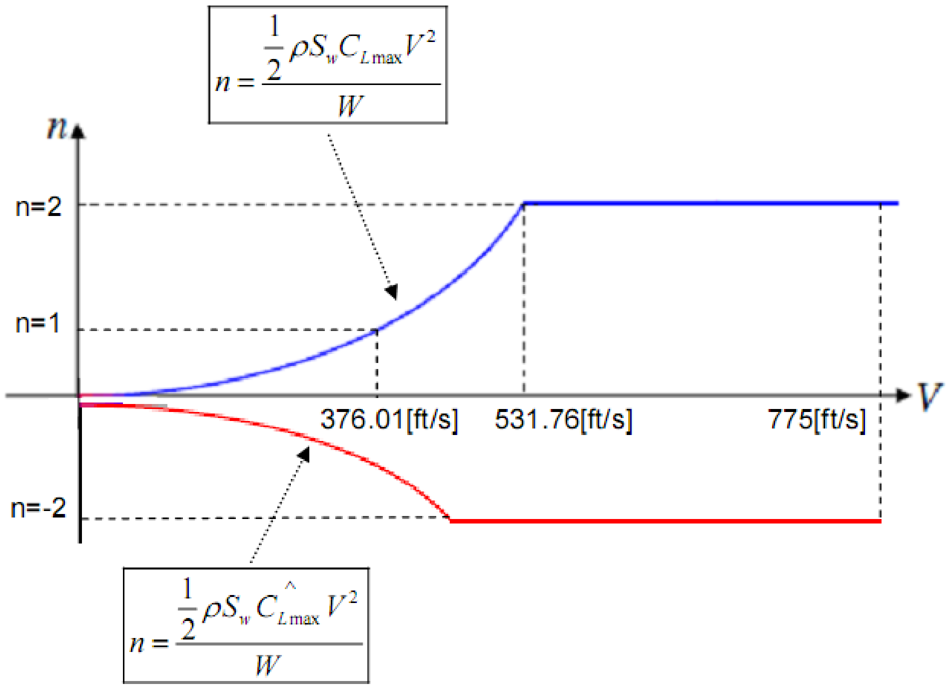

Figure 12: V-N diagram

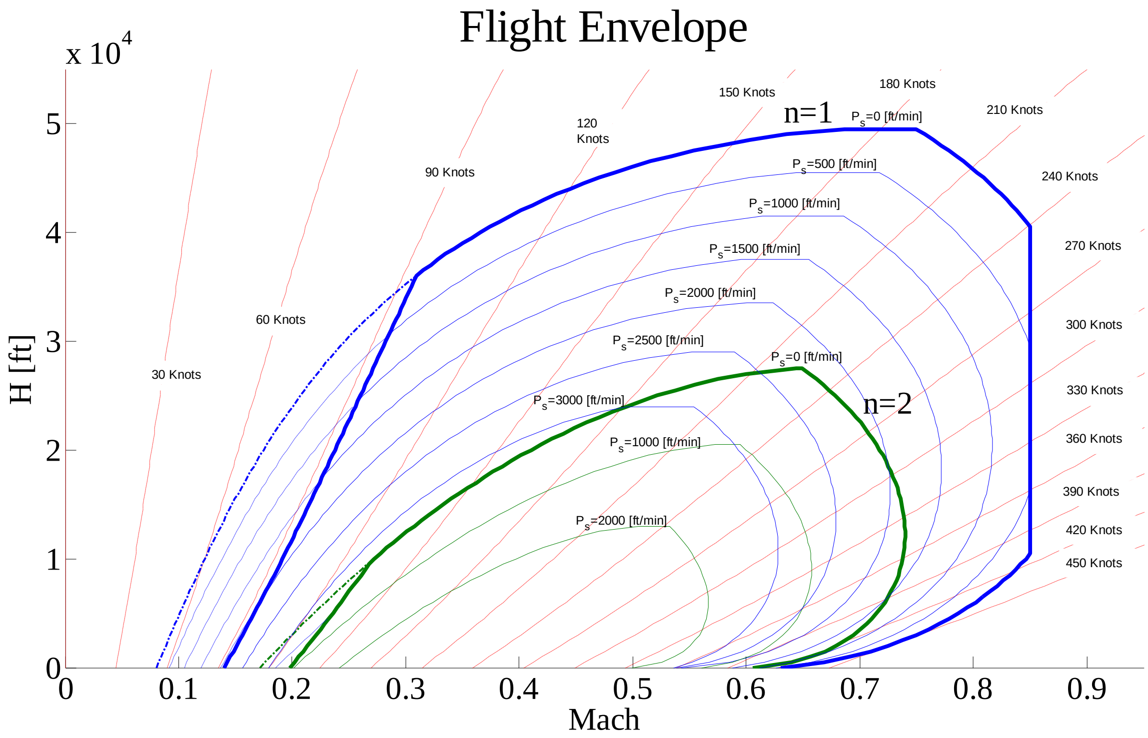

Figure 13: Flight envelope

<u>Flight control system:</u>

As seen in previous chapters the aircraft is now longitudinally stable, therefore the pitch angle control loop is easier to design:

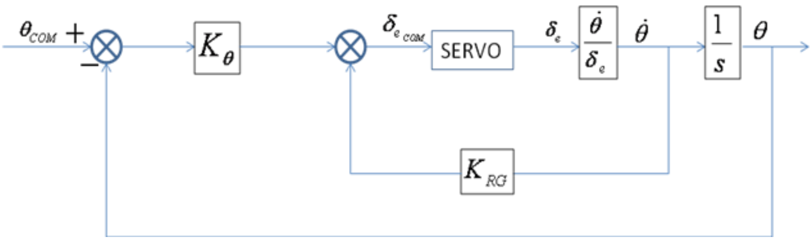

Figure 14: Pitch control loop

After gains selection the following step response is obtained:

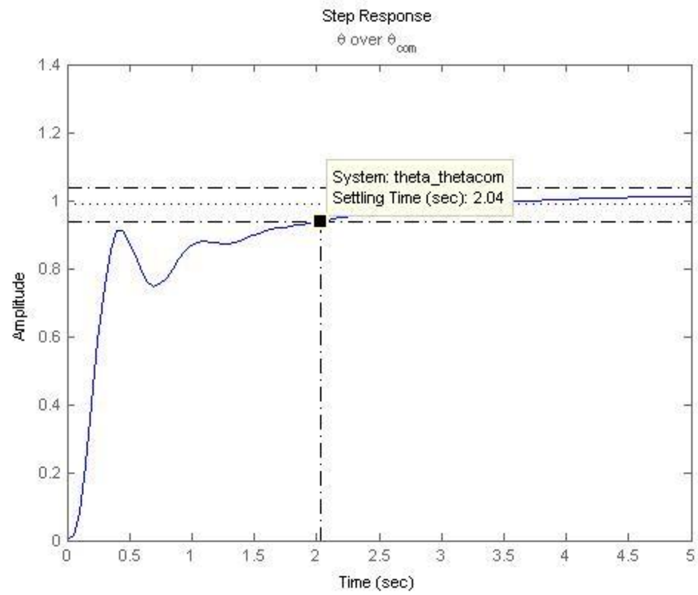

Figure 15: Pitch step response

Since the aircraft's stability margin is relatively low the step response is a bit jumpy but still admissible.

Lateral design was far more complicated. Since the UCAV has no vertical tail 1 of the Dutch roll poles has become unstable and coupled with the spiral divergence pole has lead to control loops which cannot be stabilized by any gain. In order to resolve this we employed the pole placement method, where in 1 of the controllers is set as a linear function of all state variables and, with the appropriate selection of coefficients can lead to a stable system.

However, weathercock stability was still not fully recovered, suggesting that perhaps a better method exists to control the slip angle.

Conclusions

- Both the parasitic and induced drags are slightly higher than anticipated but still are considerably low and within reasonable range.
- In terms of stability the aircraft is stable in the longitudinal plane and unstable in the lateral plane at some angles of attack, this will be dealt with in the flight control chapter.
- The aircraft's aerodynamic efficiency was according to expectation with a max L/D value of 15.4
- Successful usage of forward opening inlay spoilers for yaw control. The selected spoiler of hinge angle 35 degrees was able to produce enough yaw moment to counter parasitic yaw moment from the ailerons and also yaw moments created by slip angles, it also creates a minimal roll moment that can be easily overcome by the ailerons. However this spoiler stalls at $\alpha \cong 10^o$ which is a limiting factor for the entire aircraft that reduces $C_{L_{\max}}$. With further design it is recommended to resolve this issue by trying different positions and spoiler geometries.
- Elevons are very effective for pitch and roll control up to about 15 degrees deflections. Inner elevons can be used for pitch only, while outer ones for both pitch and roll.

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